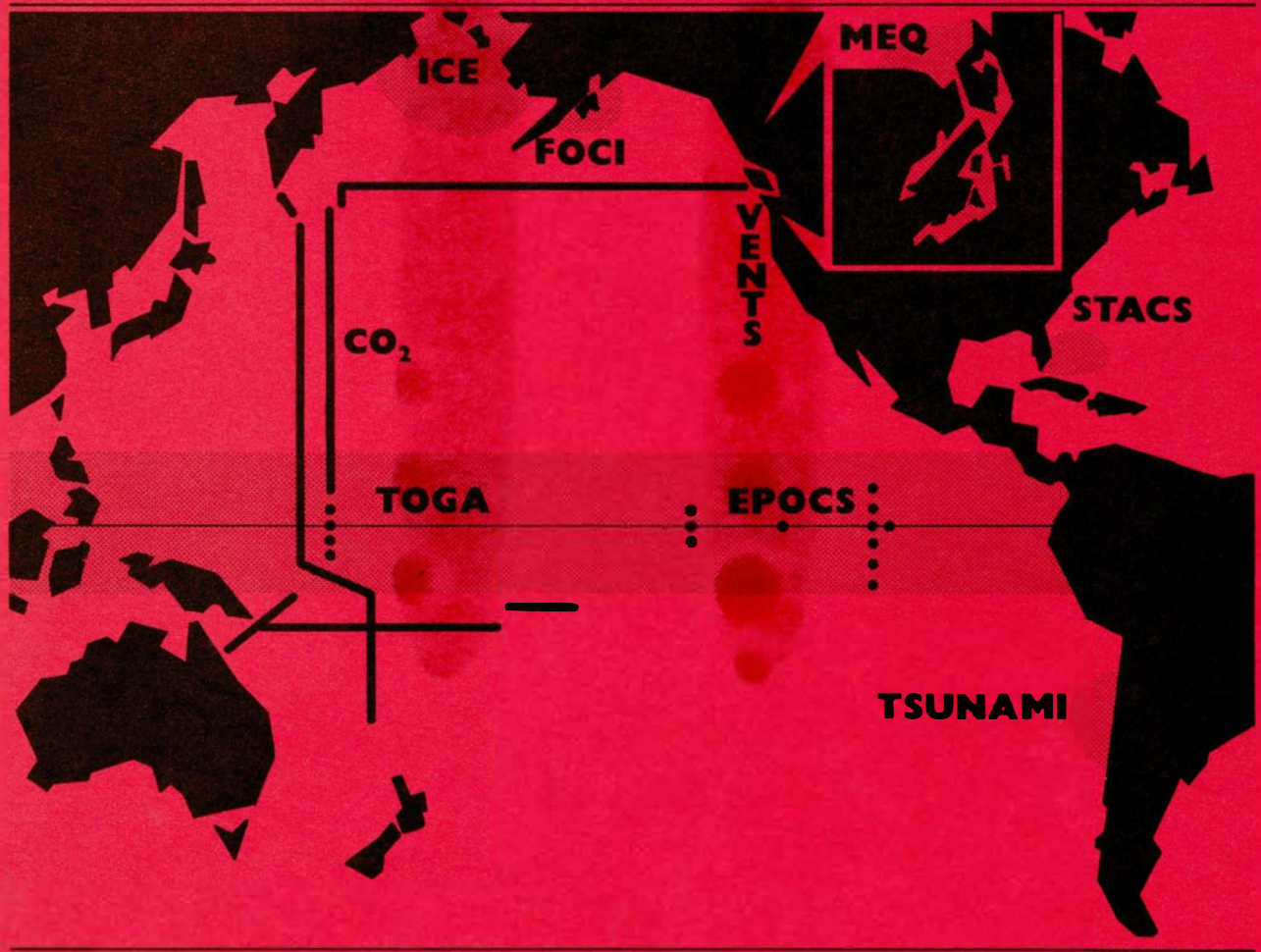
Pacific
Marine
Environmental
Laboratory

Annual Report for FY 87



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NATIONAL OCEANIC AND
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Environmental Research
Laboratories

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INTRODUCTION

The Pacific Marine Environmental Laboratory (PMEL) is one of nine research laboratories within the Environmental Research Laboratories (ERL), Office of Oceanic and Atmospheric Research (OAR) of the National Oceanic and Atmospheric Administration (NOAA). PMEL, which is located in Seattle, Washington, carries out scientific investigations in physical, chemical and geological oceanography, marine meteorology, and related disciplines in support of NOAA's missions to protect human health and safety from marine hazards and to ensure wise development of ocean resources. PMEL participates in national and international programs that focus on global climate, marine services, marine environmental quality, and marine resources. Its research goal is to improve understanding of coastal and open-ocean processes and, through observation and modeling, to develop a greater capability to monitor and predict marine environmental conditions. Laboratory programs focus on the North and South Pacific Oceans, the Bering Sea, and adjacent coastal regions.

Research conducted by PMEL scientists emphasizes 1) measurements and modeling of forcing mechanisms that drive ocean circulation and global climate, 2) understanding selected physical and geochemical processes that govern the extent and impact of human activity in the marine environment, 3) improvement of environmental forecasting capabilities and other services for marine commerce, fisheries, and recreation, and 4) investigations of physical and geochemical processes associated with formation and transformation of new marine resources at sea floor spreading centers. Products of PMEL's projects include scientific discoveries, marine assessments, environmental information, data synthesis, and models that reflect improved understanding of marine systems. These products are disseminated through refereed scientific journal articles, technical reports, and presentations at national and international meetings, academic and government institutions, and other public gatherings.

The marine environmental studies conducted at PMEL require professional scientists with a wide range of background disciplines, a strong technical support staff, and an integrated experimental and theoretical research approach that utilizes state-of-art field, laboratory, and analytical techniques. PMEL projects are often elements of larger national and international programs and, consequently, its scientists participate actively in the broader oceanographic community, serving on scientific steering committees, program planning panels, and collaborating in multi-institutional field efforts.

The scientific staff is organized into four research divisions: the Marine Assessment Research Division (MARD), the Marine Resources Research Division (MRRD), the Marine Services Research Division (MSRD), and the Ocean Climate Research Division (OCRD). Engineering, computer, and administrative expertise is provided by the Engineering Development Division (EDD), the Computer Support Group (CSG), and the Administrative Support Group (ASG), respectively. Two cooperative institutes, the Joint Institute for the Study of Atmosphere and Ocean (JISAO) and the Joint Institute for Marine and Atmospheric Research (JIMAR) estab-

lished between NOAA and the Universities of Washington and Hawaii, respectively, provide close research collaboration between the academic community and PMEL scientists working in climate dynamics, environmental chemistry, tsunami, and estuarine processes.

PMEL is located primarily in NOAA's Northwest Regional Center at Sand Point in Seattle, Washington. The assemblage of NOAA personnel and activities in Seattle is the second largest in the United States and includes elements of the National Marine Fisheries Service (NMFS), the National Ocean Service (NOS), the National Weather Service (NWS), the National Environmental Satellite, Data, and Information Service (NESDIS), and the National Sea Grant College Program. PMEL's collocation with these groups provides a unique opportunity for cooperative work and exchange of information, direct transfer of research results to NOAA's operational components, and ready access to major NOAA facilities such as the NOAA Pacific Fleet, the National Analytical Facility, the Northwest Regional Calibration Center, and the Northwest Ocean Services Center (NOSC).

There is, however, a portion of the MRRD that is located at the Hatfield Marine Science Center in Newport, Oregon. The Hatfield Marine Science Center is jointly operated by the NMFS and Oregon State University allowing for close cooperation between these elements as well as other departments of Oregon State University located nearby in Corvallis, Oregon.

CLIMATE RESEARCH

During recent years there has been an increasing awareness of the effect of short- and long-term climatic changes on resource systems, particularly food and energy, and conversely, a concern about the effect of technology and population growth on world climate. When the National Climate Program Act was passed in 1978, NOAA became the lead agency for U.S. research in climate dynamics. PMEL scientists have been heavily involved in the formulation and implementation of the NOAA Ocean Climate Program.

To predict climatic change, it is necessary to understand the processes of heat, moisture, and momentum exchange between the ocean and atmosphere, as well as the large-scale transports of heat within the atmosphere and ocean. The ocean climate research program investigates the problem in studies of both local (small-scale) and basin-wide (large-scale) ocean dynamics and the coupled ocean-atmosphere circulation. Laboratory participation in multi-institutional field experiments has established the groundwork for present efforts in two national climate programs: Equatorial Pacific Ocean Climate Studies (EPOCS) and Tropical Oceans and Global Atmosphere (TOGA). These studies are designed to test the hypothesis that sea-surface temperature (SST) anomalies in tropical regions have a pronounced effect on atmospheric circulation in both tropical and temperate latitudes. A major research goal is to determine the relative importance of the physical mechanisms that generate anomalies in sea-surface temperature distributions in the tropical ocean.

A crucial step in reaching that goal is to develop and validate ocean circulation models that are capable of simulating the evolution of such globally important events as El Niño. In 1985, the Tropical Modeling and Analysis Program (TMAP) was initiated at PMEL to study the mechanisms affecting tropical SST through the use of numerical modeling experiments and comparison of model results with ocean observations.

Heat transport by major western boundary currents (the Gulf Stream and the Kuroshio in the Northern Hemisphere) is also postulated to have an important effect on world climate. Western boundary current studies at PMEL continue to focus on the Florida Current as part of the Subtropical Atlantic Climate Studies (STACS).

PMEL also conducts two important marine chemistry research programs for NOAA under the National Climate Program. These studies relate to the ocean's behavior as a sink for atmospheric carbon dioxide (CO_2), which has been steadily increasing over the past century. One project measures the flux of anthropogenic fluorocarbons into the ocean in order to trace gas diffusion across the ocean-atmosphere boundary and within the ocean. The other project examines the role of biologically produced, particulate calcium carbonate as a sink of CO_2 at high latitudes. Together these studies will help determine the potential of the oceans for absorbing CO_2 and modifying global warming.

Accomplishments FY 1987

EQUATORIAL DYNAMICS

The ENSO Event of 1986-1987

A sparse array of equatorial current meter moorings at 110°W, 140°W, and 165°E has provided time series data of upper ocean currents, temperatures, and surface winds for the purpose of studying equatorial dynamics and air-sea interaction. The 110°W and 140°W sites have been maintained as part of NOAA's EPOCS program in the eastern Pacific, and the 165°E site as part of the U.S./P.R.C. bilateral oceanographic and meteorological program in the western Pacific.

Measurements made from the current meter moorings documented the evolution of equatorial wind, current, and temperature fields during the 1986-1987 El Niño/Southern Oscillation (ENSO) event. Surface temperature and, in some cases, wind observations were telemetered via satellite in real time to provide information on the day-to-day evolution of the event. The 1986-1987 ENSO was much weaker than the 1982-1983 ENSO and evolved differently from the prototypical ENSO events that show a westward progression of warm sea-surface temperatures from near the South American coast into the interior ocean. By contrast, significant and persistent warming in 1986 first appeared in the central Pacific and later along the South American coast. Warming in 1986-1987 was related to the weakening of the trade winds west of the dateline, and to a reduction in the zonal slope of the thermocline and of sea-level difference across the basin. Eastward current transports associated with the Equatorial Undercurrent weakened in late 1986 and early 1987 at 110°W and 140°W, but the Undercurrent did not disappear as in early 1983. A complete analysis of the observations awaits the termination of the event; the 1986-1987 event is the best documented ENSO event on record.

Seasonal and Intraseasonal Variability

Data from equatorial moorings at 110°W, 124.5°W, and 140°W for the period 1983-1986 were used to examine the dynamics of wind-forced equatorial variability during non-El Niño years. It was found that there is an approximate balance between zonal wind stress and the zonal pressure gradient for the annual mean, for the one cycle per year harmonic, and for a low-frequency trend from 1983 to 1986. Nonlinearity is important in producing an Undercurrent that shoals to the east in the thermocline and in increasing eastward transport at the Equator relative to that expected from linear theory. The springtime South Equatorial Current reversal at the surface is shown to be the result of a rapid relaxation of the trade winds in the eastern Pacific in boreal winter. Also, highly energetic, eastward-propagating Kelvin-wave-like 60-90 day waves were documented in zonal currents and dynamic height. These intraseasonal fluctuations are probably related to wind forcing west of the dateline at similar frequencies.

The Response of the Equatorial Ocean to a Westerly Wind Burst

Westerly wind bursts of 1-3 weeks duration in the western Pacific are potentially important in triggering and sustaining ENSO events by means of Kelvin wave excitation and associated eastward advection of warm water. One such burst of 10 days duration, accompanied by Northern and Southern Hemisphere cyclone pair formation, occurred in May 1986 west of the dateline (180°W). The response to this burst was documented from current meter mooring, thermistor chain mooring, sea level, and hydrographic data. The local response in the western Pacific was both rapid and dramatic. The South Equatorial Current reversed and reached speeds in excess of 100 cm s^{-1} to the east at 100 m depth within a few days of the wind reversal. A sharp Kelvin-wave-like pulse subsequently propagated eastward out of the directly forced region, reaching the coast of South America about 45 days later. However, the pulse had little lasting effect on sea-surface temperature in the eastern Pacific because it was not associated with strong anomalous surface currents. Thus it appears that the May 1986 wind burst did not significantly influence the evolution of the 1986-1987 ENSO as had been speculated at the time of its occurrence.

Transports of Equatorial Water

From 5 June to 6 July 1987 the *Oceanographer* completed the western segment of the transpacific section along 15°S. This was the first tropical section to span the Pacific and was designed to study heat, freshwater, and chemical tracer transports into the equatorial region from the subtropical gyre of the South Pacific. A total of 109 CTD/chemistry stations were occupied, and most casts reached the bottom. Preliminary analyses have indicated a wealth of new information on the circulation of the western South Pacific. Subsurface (200-1000 m) boundary currents along the Great Barrier Reef and the Louisiade Archipelago were identified, which bring high-salinity water northward into the Solomon Sea and eventually supply water to the Equatorial Undercurrent. Abyssal circulation was also explored, and findings indicated near-bottom meridional currents along the boundary of each of the major basins. At intermediate depths the characteristics of Antarctic Intermediate Water (AAIW) indicated an interesting east-west change along the section. This water mass is formed at, and north of, the Circumpolar Front, enters the subtropical gyre, and flows northward. It is characterized by a salinity minimum and oxygen maximum at depths of 500 m to 800 m.

Since the 15°S section essentially paralleled the eastward-flowing northern branch of the subtropical gyre through much of the mid-Pacific, it was expected that, from east to west, the AAIW would become, through mixing, gradually saltier and lower in oxygen. Instead, the oxygen content actually increased abruptly near the dateline. The salinity correspondingly decreased, and it might be inferred that the water in the western part of the section was newer. This interpretation was supported by the chlorofluorocarbon (CFC) measurements that were also collected. The ratio of CFC-11 to CFC-12 gives an estimate of the age of the water, i.e., how recently this water was exposed to the surface. East of 170°W a large fraction of the AAIW had a CFC age of >35 years; west of the dateline the water was 10-15 years younger. These measurements indicated that a branch of AAIW is injected into the subtropical gyre in the western Pacific, perhaps east of New Zealand near the Chatham Rise. This water flows northward and

may provide a significant fraction of the AAIW in the western Pacific. Understanding this circulation is important in defining the heat and salt transports of the South Pacific.

Observations of the Tropical Pacific Thermal Field

As part of the TOGA and EPOCS projects, an array of ATLAS (Automated Temperature Line Acquisition System) moored thermistor chains and wind sensors has been maintained in the tropical Pacific from 165°E to 110°W that has provided data in real time via satellite link. Such data are important in the diagnostic study of ocean conditions and for comparison with numerical model simulations. During FY 1987, comparison was completed of the measurements with the quasi-real-time NMC ocean model simulation being run at the National Meteorological Center (NMC). Comparisons of SST depths of the 20°C and 15°C isotherms, and upper ocean heat content have been carried out for several locations in the eastern Pacific. The agreement between model and data is fairly good for isotherm depths and heat content north of the Equator, but SST is not well represented by the model. South of the Equator the SST representation is better, but the isotherm depth changes are not as well characterized. Comparisons such as these have led to improvements in the model simulations, particularly through assimilation of data into the model. In these assimilation studies at NMC, the ATLAS moored data are withheld from the assimilation and are used to check the model results. Comparison time series show great improvement in the model thermal field. These studies are encouraging indications that an operational numerical model that accurately simulates the real ocean is developing quickly.

Tropical Wind Variability

The large-scale, interannual, seasonal average wind variability between 850 mb and 150 mb of the eastern tropical Indian Ocean and western/central tropical Pacific has been examined using station wind soundings for 1961 to 1983. A very large eastward-propagating anomalous pattern of winds was identified using complex empirical orthogonal function (EOF) analysis; this pattern was associated with each of the post 1960 ENSO events. Significant anomaly amplitude was found to have existed well before any eastern Pacific surface warming. The variation of the evolution of wind anomalies from event to event was considerable, but a significant eastern Indian Ocean anomaly was found in the September-October-November season prior to eastern Pacific surface warming for every event except 1969. The early stages of the 1982-1983 event looked very much like those of most other events in the western Pacific. This EOF pattern offers a possible climate statistic to monitor for ENSO forecasting.

Monthly mean island surface wind anomalies near the dateline (180°W) associated with ENSO events were examined for 1953 to 1980. It was found that three aspects of wind variation are common to all the ENSO events (except 1969). (1) Westerly anomalies appear first west of the dateline and then at the dateline sometime in summer of the year of eastern Pacific warming. These anomalies intensify over the following several months, and are largely confined to within 3° latitude of the Equator. (2) Some time between the following November and January there is an abrupt shift of the narrow westerly anomaly pattern southward, with the anomaly pattern centered near 5°S; nearly normal conditions prevail north of the Equator. (3) Westerly anomalies

are gone or greatly reduced 1 to 2 months after the southward shift. It was also found that the composite anomaly field significantly underestimated both the magnitude of the anomalies and the month-to-month changes in anomalies, compared with what is observed typically in any particular ENSO event. It was also found that significant differences exist between the island wind composite anomaly and that described by Rasmusson and Carpenter in 1982.

Ocean Model Hindcasts of the 1982-1983 ENSO Event

Five different analyses of 1982-1983 monthly average surface wind stress fields have been used to force an ocean general circulation model of the tropical Pacific, in a series of El Niño hindcast experiments like that reported by Philander and Seigel in 1985. Operational surface wind analyses were produced by the meteorological centers: National Meteorological Center (NMC), European Center for Medium-range Weather Forecasting (ECMWF), and Fleet Numerical Ocean Central (FNOC). Special research product analyses were produced by Florida State University and Sadler. The results of the hindcasts were compared with the variability of upper-ocean dynamic height, sea-surface temperature, and subsurface temperature as observed from XBT data obtained along the three main ship-of-opportunity tracks.

The ocean underwent several major changes during this period according to the XBT data. The model hindcasts were examined to determine the extent to which the observed major ocean changes were reproduced. Within the equatorial waveguide, the best hindcasts differed from the observations by only a few dyn-cm more than the estimated uncertainty in the observations. The high skill in hindcasting dynamic heights in the equatorial waveguide indicated that the major features of the 1982-1983 El Niño were contained in the 1982-1983 surface wind stress field, rather than in any particular aspect of the state of the ocean during late 1981. Sea-surface temperature changes were generally hindcast with some qualitative skill; the correlation between hindcast and observed SST was usually significantly positive, but the RMS difference between any hindcast and the observations was generally greater than the RMS signal in the observations. Subsurface temperature variability was hindcast with differing levels of skill, depending upon stress field, region, and depth. The vertical temperature gradients and mixed-layer temperatures, as well as the depth of the thermocline, underwent substantial changes (especially in the eastern Pacific); primitive equation physics appear necessary to model these observations.

Outside the waveguide, hindcast skill was generally much reduced; although qualitatively correct behavior was often hindcast, amplitudes could be seriously in error. The most striking inconsistency involved the NMC hindcast in the region of the North Equatorial Countercurrent. The special research products generally gave more accurate hindcasts of dynamic height, but the operational fields often produced better SST hindcasts. A clear deficiency of the operational fields was the character of their wind stress curl fields, compared either with climatology or the special research analyses. Because Ekman pumping is a major factor in thermocline adjustment outside the waveguide, wind stress curl must be correctly represented if adequate hindcasts are to be obtained.

Although improved parameterization of upper-ocean mixing, and better knowledge of the surface heat flux appear needed to improve SST hindcast skill, these results establish that a most serious need for improved hindcast performance is better knowledge of the surface wind stress field.

WESTERN BOUNDARY CURRENTS

The transports of the Florida Current derived from the cross stream voltages between Jupiter, FL, and Settlement Point, Grand Bahama Island, continued to be observed. The clean cut at the cable break carried out at the end of 1985 has removed all sudden voltage offsets, and the earlier calibration has been verified by comparisons with transports derived from 1986 velocity profiling data. This unique 6-year series of transports has been compared with transports derived from a numerical model driven by the monthly winds over the North Atlantic and Caribbean. The comparisons showed that the mean and seasonal variations of the model-derived transport are low by a factor of 1.7. When the model was corrected, the seasonal variation of the cable- and model-derived transports were in agreement at the 95% level. The cable-derived transports are now being used for model verification and improvements.

The study of active telephone submarine cables for transport measurements is also continuing, using a cable between West Palm Beach, FL, and Eight Mile Rock, GBI, some 20 miles south of the passive cable. It has been established that the temperature variations at the Eight Mile Rock cable station are not the cause of the discrepancy in transports between the active and passive cables. Instead, the discrepancy is probably caused by variations in the cable station ground. Transfer functions are used to remove the geomagnetically induced voltages from the observed cable voltages using remote magnetic time series observations. The research to derive reliable transfer functions will enhance the accurate removal of unwanted geomagnetically induced variations. The improved transfer functions will also be used to estimate mantle conductivities that are needed to developed electromagnetic models.

TRACE GAS/CLIMATE CHANGE

CARBON DIOXIDE/RITS

One of the significant environmental issues of the next century will be systematic changes in the Earth's climate due to increases in the atmospheric burden of CO_2 and other greenhouse gases including methane, CFCs, and carbon monoxide. The secular increase in CO_2 is the result of the burning of fossil fuels and massive deforestation currently under way. For a given rate of fossil fuel combustion, the observed rate of increase in the atmospheric CO_2 burden is thought to depend primarily on the rate of ocean uptake. This oceanic influx depends in turn upon the detailed space- and time-dependent air-sea exchange of CO_2, the oceanic processes of thermocline ventilation, and the action of the marine biological "pump" by which carbon is fixed in particulate form in near-surface water, settles, and then decomposes at depth.

In 1987 the CO_2/RITS cruises were conducted in the western Pacific in the early spring and late summer. The spring cruise, along 160°E between Kamchatka and New Zealand, was part of the

U.S./U.S.S.R. bilateral research program in the western Pacific aboard the Academik *Korolev*. The summer NOAA cruise aboard the NOAA Ship *Oceanographer* along 165°E between Australia and Alaska, was a reoccupation of a 1982 cruise track. The data from both cruises indicated that the western Pacific is a region of intense ventilation of the upper 1000 meters of the water column. In early spring, PCO_2 concentrations in surface waters near 47°N exceeded 400 µatm and were nearly constant to a depth of about 200 meters. These high values were probably the result of enhanced vertical mixing of surface and subsurface waters in winter because of the increased storm activity. In late summer, PCO_2 concentrations in surface waters were well below saturation values throughout most of the study region. These large and widespread seasonal variations in the PCO_2 concentrations of the northwest Pacific are affected by several physical and biogeochemical processes acting concurrently. These include (1) the seasonal fluctuations in the temperature of the water column, which directly affect the solubility of CO_2 in seawater; (2) the seasonal changes in vertical mixing of the water column, which can cause entrainment of subsurface waters into the mixed layer; and (3) the seasonal drawdown of CO_2 in surface waters due to photosynthesis. The results to date indicate that CO_2 concentrations in surface waters represent a delicate balance between these processes. Vertical mixing and entrainment processes predominate in winter, and photosynthetic uptake of CO_2 predominate in spring and summer.

The distributions of CFC-11 were combined with precise measurements of total CO_2, total alkalinity, oxygen, and nutrients to provide estimates of the amount of fossil-fuel-derived CO_2 in the surface and intermediate waters of the North Pacific. The approach uses the CFC-11 profiles to determine the apparent vertical mixing parameters. These parameters were used in a horizontally averaged, one-dimensional vertical diffusion model along with the CO_2 source function to provide model predictions of anthropogenic CO_2 concentrations. These predictions were compared with estimates based on station data. The results show good agreement between the modeled profiles and the calculated data for all stations in the central gyres. The calculations indicate that 15×10^{15} g excess carbon now resides in the mixed layer and thermocline waters of the North Pacific.

CFC Tracers

Unique among the climate-forcing trace gases are the chlorofluorocarbons, with no natural sources and no significant sinks other than ultraviolet photolysis in the stratosphere. The current ocean burden of CFC-11 and CFC-12 is about 1% with respect to the atmosphere; the steady-state capacity of the global ocean is about 20%. The principal utility of CFCs in the sea is accidental, namely, as a time-dependent tracer of water mass formation and thermocline ventilation, which are critical processes for assessing the moderating role of the oceans in delaying and damping the global warming predicted for coming decades.

The CFC tracer measurements made aboard the joint U.S./U.S.S.R. expedition of the *Korolev* off the coast of Kamchatka offered a first look at the source regions of the North Pacific Intermediate Waters, the major pathway for ventilating the main thermocline of the entire North Pacific. The Southern hemisphere equivalent of the North Pacific Intermediate Water (NPIW) is the Antarctic Intermediate Water (AAIW) within which a strong CFC tracer signal was found on

both the *Korolev* Expedition south of Australia and during the transpacific section at 15°S from Tahiti to Townsville (the TEW expedition of the NOAA Ship *Oceanographer*).

Progress was made in development of a technique for CFC post-cruise analysis of samples stored in crimped copper tubing. The technology for sampling and shipboard analysis of CFC tracers was shared with Soviet colleagues during the *Korolev* cruise, and future ocean climate/trace gas expeditions are being planned.

A significant finding from the 1987 field season is that the 5-year increase in the thermocline burden of CFC tracer in the western Pacific (1982-1987) is much less than that observed in the eastern side of the basin during a comparable interval (1981-1986).

Marine Sulfur

It is becoming increasingly evident that oceanic biogenic sulfur emissions influence the climate of our planet by controlling the acidity and number population of marine atmospheric aerosols. It is believed that almost all the submicrometer-sized aerosol particles in the remote marine troposphere are derived from dimethylsulfide (DMS), which is produced by phytoplankton in the surface waters of the ocean. The PMEL marine sulfur research program seeks to (1) quantify the ocean's role in the tropospheric sulfur cycle, (2) study the processes controlling oceanic DMS emissions, and (3) explore the relationship between oceanic DMS emissions and the submicrometer-sized-particle population in the atmospheric marine boundary layer.

The PMEL RITS/Acid Rain program is part of an ongoing, interagency effort to assess the natural sources of sulfur and nitrogen to the atmosphere, and is specifically intended to further the understanding of the role of the ocean in global and regional sulfur and nitrogen cycles. Reduced sulfur and nitrogen compounds are produced biologically in the surface ocean. These compounds escape to the atmosphere where they form ammonium sulfate aerosols. These atmospheric aerosols have an important role in determining the acidity of rainfall, the optical depth of clouds, and hence the albedo of the Earth. The PMEL program is designed to measure oceanic and atmospheric concentrations of sulfur and nitrogen. This project is coordinated with University of Washington and NOAA Aeronomy Laboratory scientists making similar measurements onshore.

In FY 1987, the Marine Sulfur Program at PMEL broadened in scope from a coastal view of regional onshore fluxes of natural oceanic sulfur in relation to anthropogenic acidity to a more global view that marine sulfur might have a climatically significant role in controlling cloudiness over the sea. From the accumulated multiyear surveys of marine sulfur in the North and South Pacific, a revised global sulfur budget was assembled. In the laboratory, a working prototype of the Johnson-Lovelock detector was constructed that has a gain of more than 2 orders of magnitude over existing trace sulfur systems. Detailed and continuous trace sulfur measurements were made during the U.S./U.S.S.R. joint expedition in the Western Pacific and Indian Oceans (April-July 1987), the first such measurements in the remote Southern Hemisphere in the winter season, and the first of any kind in the Indian Ocean. Later, aboard the NOAA Ship *Oceanographer*,

detailed latitudinal distributions of trace sulfur species were made from 12°S to 55°N along 165°E.

Plans FY 1988

EQUATORIAL DYNAMICS

- Begin collection of conductivity (salinity) time series measurements and real-time near-surface current time series measurements from EPOCS equatorial current meter moorings.

- Participate in a new EPOCS field program to study ocean-atmosphere interaction in the Pacific North Equatorial Countercurrent/Intertropical Convergence Zone.

- Add ATLAS mooring at 170°W and current meter mooring at 150°E to equatorial Pacific waveguide array.

- Analyze data collected along 15°S in the western Pacific and combine data with the *Researcher* 15°S section in the eastern Pacific to provide a transpacific description of the water mass properties.

- Compare annual variation of temperature in the tropical Pacific with the general circulation model annual variation and determine what are the physical processes responsible for the annual variation of temperature.

- Use current meter and ATLAS mooring data in ocean general circulation model validation and data assimilation studies.

- Use the general circulation model to analyze the dynamics of the wave response of the ocean to impulsive forcing of the western Pacific.

WESTERN BOUNDARY CURRENTS

- Improve the voltage-derived transports by modifying the voltage-recording backup system and by installing a magnetometer at AOML for removing geomagnetically induced variations in real time.

- Improve the transports derived from the active cable voltages by installing a separate Ag-AgCl sea-earth ground at the West Palm Beach cable stations and by recording the voltage differences between this new ground and the cable station ground. This experiment will establish whether a separate ground can improve the accuracy of voltages recorded from an active telephone cable.

TRACE GAS/CLIMATE CHANGE

- Establish a major facility at PMEL for measuring and interpreting transient tracers (CFCs) in the North and South Pacific. This facility will more than double the existing annual capacity for CFC sample analysis, extending the tracer coverage to ships of opportunity operating in the remote and poorly sampled Southern Ocean.

- Continue the program of repeated meridional sections of the Pacific Ocean in order to capture the time-dependent, basin-wide distributions of anthropogenic chemical tracers (CO_2, CFCs, etc.) entering the thermocline.

- Initiate a program of modeling the measured transient tracer fields in the North Pacific thermocline (1981-87) using the GFDL ocean general circulation model.

- Develop a state-of-the-art analytical system for automated, precise determination of total CO_2 in seawater by the coulometric method.

- Refine, document, and replicate the prototype underway system ("data logger") for the automated and continuous measurement of critical atmospheric and oceanographic parameters required to interpret the air-sea exchange and marine photochemistry of climate-forcing trace species.

- Extend the suite of measured RITS species by initiating cooperative studies of oxides of nitrogen and photochemically reactive hydrocarbons.

- Design and carry out cooperative field programs that aim to quantify the relationship between the flux of marine sulfur (DMS) to the atmosphere, and the local atmospheric abundance of the sulfate aerosol particles thought to control cloudiness.

- Improve analytical methods for determining ammonia at natural levels in seawater and rainwater, and in the atmosphere.

MARINE ENVIRONMENTAL ASSESSMENT

Marine environmental assessment at PMEL emphasizes understanding the complex physical and geochemical processes that ultimately determine the health of marine systems and their ability to assimilate contaminants. Included are studies of the geochemistry of trace metals and organic compounds, distributions of hydrocarbons and synthetic organics, coastal and estuarine circulation, and modeling of transport processes. Although the geographic focus of these studies has been Pacific Northwest and Alaskan coastal and estuarine waters, the scientific knowledge acquired and methodologies developed are applicable to other marine systems.

Accomplishments FY 1987

LONG-RANGE-EFFECTS RESEARCH

In response to the Marine Protection, Research and Sanctuaries Act of 1982 and the National Ocean Pollution Research and Development and Monitoring Planning Act of 1978, PMEL has addressed environmental concerns associated with transport and marine disposal of municipal and industrial wastewater and the reaction of marine systems to continuous influx of contaminants. PMEL is examining the role of suspended particulates in transporting contaminants and in removing them from marine systems. Researchers have been investigating the mechanisms by which heavy metals and organic pollutants partition between water and particulates and are subsequently buried in sediments or advected from the estuary in dissolved form. As these processes become better understood, the long-term effect of chronic, low-level input of pollutants into the marine system will be assessable. Therefore, studies in the Puget Sound-Strait of Juan de Fuca estuarine system, under way for many years, are leading to a better understanding of the ability of estuaries to accommodate pollutant inputs.

In 1987, increased emphasis was placed on simulation modeling of the present data base and on geochemical process studies; descriptive physical and chemical field studies have been temporarily suspended while an assessment was conducted of data and knowledge gaps. This refocusing has led to a new 5-year Implementation Plan for Marine Environmental Quality at PMEL.

Estuarine Circulation

Puget Sound is the southernmost glacially carved estuary in western North America and is surrounded by major urban centers. The entrance sill to this estuary has a major role in regulating the replacement of water inside the estuary below the sill. Although salinity (density) at sill depth outside the estuary is always greater than inside, water from outside does not flow continuously into the Sound. Previous studies showed bottom-water inflow events during neap tides when mixing is least over the entrance sill. Other studies, however, had implied that inflow

occurred on very large spring tides when the tidal excursion could transit the sill on a single flood tide. Recent observations have shown that this circulation feature is exceeded only by wind effects.

At about fortnightly intervals there is a pronounced increase in salinity just inside the entrance sill. This is the dominant characteristic of inflow of new bottom water. The onset of these intrusions occurred in all cases before minimum neap tidal currents. Inflow during the largest intrusions is sufficiently strong that the currents at the bottom do not reverse at tidal intervals. Spring tides all coincided with decreasing salinity in the basin. Thus, it seems clear that major inflows occur only during neap tides, but the onset occurs before the minimum neaps.

Because of the relatively large variation in outside salinity and because the increase in inside salinity occurred before neap tides, it seemed possible that variations in the pressure gradient across the sill had a role in the onset of the intrusions. A quasi-steady-state balance between the pressure gradient and vertical mixing predicts currents about the same as those observed. A change in salinity of 1.4 parts per thousand is about what would be required to initiate intrusions.

Estuarine Transport

Trace metals in estuaries are derived from natural and human sources. They can be viewed not only as contaminants, when in toxic concentrations, but also as independent tracers of transport in the water column and in sediments. The assimilative capacity of estuaries for individual trace metals is a function of the balance between input and removal processes. This balance may be viewed as a dynamic equilibrium between input and removal on a decadal time scale. This view is useful for analyzing long-term trends and establishing the dominant processes. However, these trends cannot be simulated and predicted without information on rapid geochemical processes, since the underlying circulation models themselves incorporate high-frequency physical processes. These problems are being addressed over both long and short time scales.

During 1987, PMEL scientists completed individual dissolved and particulate mass balances for Mn, Pb, Cu, and Zn in Puget Sound. This is the first time individual dissolved and particulate mass balances have been simultaneously constructed for a U.S. estuary. The results quantify the effects that geochemical reactions have on the fate of trace metals discharged into the marine environment. The rapid recycling of Mn between the water column and the sediments produces large quantities of hydrous manganese oxide particles, which can absorb other trace metals. The enrichment of Pb on Mn-rich particles indicates that dissolved Pb is being scavenged onto the newly formed hydrous manganese oxides. The mass balance calculations indicate that 70% of the dissolved Pb discharged into the main basin of Puget Sound is being scavenged onto particles. This extensive scavenging results in retention of 72% of the total Pb in the sediments of Puget Sound while only 28% is advected from the main basin. In contrast, Cu and Zn do not appear to be appreciably scavenged by manganese oxides particles, and their fate is determined mainly by the geochemical form (dissolved or particulate) of the source material. Only 40% of the Cu and Zn added to the main basin is retained in the sediments while 60% is advected from the main basin. For Cu, the complexation by dissolved organic matter seems to prevent its

scavenging. Between 30% and 70% of the dissolved Cu was found to be complexed with dissolved organic matter.

Although important geochemical processes can be inferred from field observations, laboratory studies are usually needed to delineate the mechanisms and rates of the individual reactions involved in these processes. Knowledge of the rates of geochemical reactions is essential to the accurate modeling of trace metal behavior in estuaries. Laboratory studies on the rates of two important geochemical processes were initiated during 1987. The kinetics of Mn oxidation was investigated using unaltered Puget Sound seawater. Preliminary attempts to model Mn in estuaries have indicated that the kinetic oxidation constants derived from these experiments will become a critical part of any successful model developed at PMEL. Experiments were also initiated to investigate Cu's reactivity toward dissolved and particulate organic matter.

Until recently the study of the behavior of polycyclic aromatic hydrocarbons (PAH) was a major feature of our estuarine studies. The data gathering has ceased but analyses will be published over the next few years. PAHs are toxic compounds generated by the combustion of coal, oil, wood, gasoline, and other organic materials. PAHs are hydrophobic and exist largely in particulate form. The unresolved complex mixture (UCM) is a measure of uncombusted petroleum hydrocarbons and can be found in particulate and dissolved forms. These two compound classes are good indicators of human impact on the marine environment. During this past year, PAH and UCM concentrations on suspended particles and sediments were combined with sediment deposition rates and circulation data to quantitatively assess the transport and fate of hydrocarbons in Puget Sound. The findings from this study indicate that >93% of the hydrocarbons associated with suspended particulates in the main basin of Puget Sound are deposited in the estuarine sediments. Approximately 63% of the particulate PAH and 100% of the particulate UCM that are deposited in the sediments settle directly to the sediments from surface waters. The remainder of the PAHs that are deposited to the sediments arrives by horizontal transport from other areas.

PAHs were also quantified on suspended particulate matter in Elliott Bay to evaluate the importance of combined sewer overflows as a source of these compounds. PMEL findings show that, although such events occur in Elliott Bay only 10-20 times each year, each event supplies a significant quantity of PAHs to the bay. The results of these two studies of hydrocarbon concentrations on suspended particles enabled PMEL scientists to construct the first balanced budget for PAHs in Puget Sound.

Chlorinated hydrocarbons are toxic compounds that have been routinely used as pesticides and in industrial applications. The conventional technique of analyzing chlorinated hydrocarbons by gas chromatography often overestimates their concentration. In the last year PMEL scientists developed a more reliable method using the positive identification technique of gas chromatography/mass spectrometry. The generally low levels of chlorinated hydrocarbons observed in Elliott and Commencement Bays are consistent with decreased use of these compounds. DDT use was banned in 1972, and the use of polychlorinated biphenyls has been greatly curtailed since 1976. Elevated concentrations of chlorinated hydrocarbons were found, however, near sewage outfalls and in waterways where major spills are known to have occurred. These

occurred on very large spring tides when the tidal excursion could transit the sill on a single flood tide. Recent observations have shown that this circulation feature is exceeded only by wind effects.

At about fortnightly intervals there is a pronounced increase in salinity just inside the entrance sill. This is the dominant characteristic of inflow of new bottom water. The onset of these intrusions occurred in all cases before minimum neap tidal currents. Inflow during the largest intrusions is sufficiently strong that the currents at the bottom do not reverse at tidal intervals. Spring tides all coincided with decreasing salinity in the basin. Thus, it seems clear that major inflows occur only during neap tides, but the onset occurs before the minimum neaps.

Because of the relatively large variation in outside salinity and because the increase in inside salinity occurred before neap tides, it seemed possible that variations in the pressure gradient across the sill had a role in the onset of the intrusions. A quasi-steady-state balance between the pressure gradient and vertical mixing predicts currents about the same as those observed. A change in salinity of 1.4 parts per thousand is about what would be required to initiate intrusions.

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refractory compounds are apparently still present in municipal pipes and in the sediments of some locales, and continue to be supplied to Puget Sound in small quantities.

Laboratory investigation of the settling characteristics in seawater of sewage sludges from four different treatment plants was completed. The study differed from previous work in several ways: The entire size spectrum of sludges was studied including the approximately 20% by weight of particles with diameter greater than 64 μm; the fine material was allowed to flocculate under lower shear conditions than those used in previous experiments, more representative of oceanic discharge conditions; settling was measured under very low concentrations (~10 mg/L) so that flocculation would not continue during the measurement period. The results indicate that most of the sludge should settle in the ocean, barring further in-situ processing, at speeds between $\sim 10^{-2}$ and $\sim 10^{-4}$ cm/s. The coarse fraction settles at speeds of $\sim 10^{-2}$ to ~1 cm/s.

A field study of the variability of entrainment rates of fine sediment in Puget Sound was conducted in collaboration with the EPA. Measurements were made with a portable shipboard device that resuspends sediment taken from box cores. A time series of resulting entrainment data was used to infer the rates of erosion as a function of the imposed bed stress. The results are consistent with a thin, easily resuspendable layer underlying a less erodable layer. Spatial differences in erosion rates were unresolvable at the level of definition possible with this device. The results have utility in a regional model of the transport of sediment through the boundary layer of the main basin of Puget Sound.

Modeling

Theoretical studies of the transport of tides and tidal currents in Puget Sound using a model incorporating channels with multiple connections of the Sound have been completed. The results show good agreement with tidal height and phase distributions measured by tide gauges at numerous sites in the Sound. Transport estimates made from current meter data for four cross-axis transects on which there were multiple moorings are found to be within a few percent of the model transports even though there is up to a factor-of-3 variation in the tidal currents across the channel. Energy dissipation calculations with the model show an M2 tidal dissipation of 220 MW, 75% of that occurring in Admiralty Inlet and in The Narrows near Tacoma, areas of highest currents.

The model results will be used to tune a laterally averaged, baroclinic model under development. The purpose of this numerical model is to provide a tool for understanding and predicting the distributions and evolution of physical and trace metal constituents in the main reaches of Puget Sound. Of particular interest are the effects of biweekly intrusions that renew bottom waters, and actively exchange trace metals with the underlying sediment. The emphasis during FY 1987 was on the formulation of the model for the physical processes that are responsible for the onset and character of intrusions.

The bottom boundary layer model (one-dimensional numerical model with turbulence closure) provided synthetic bottom stress data, which were fit to a new set of empirical formulas to predict the bottom stress due to steady barotropic currents in water of finite depth. Accurate

formulas are needed for the bottom stress because the erosion of sediment and associated trace metals is a sensitive function of this stress. The formulas show that the coefficient in the drag law depends strongly on the total depth and the bottom roughness.

A new way was found to apply analytic estuarine theory to the mean circulation in Admiralty Inlet, which is the main entrance to Puget Sound. The approach used the vertical eddy viscosity (found by fitting the bottom boundary layer model to the vertical profiles of tidal currents) and the mean distribution of salinity to predict the intensity of horizontal mixing in the inlet. The results show that advection is responsible for 90% of the mean horizontal transport in Admiralty Inlet, an amount significantly larger than previous estimates based on surface currents and vertical salinity profiles.

Through a study of the conservation of freshwater and salt, the mean annual transport was deduced, for the first time, over several years at all 10 sites in the Strait of Juan de Fuca/Puget Sound estuarine system. For each site, composite current profiles have been constructed from several years of observations. These provide kinematically correct weighting functions which, when applied to salinity observations, yield the correct two-layer salinities required for mass transport calculations. An error analysis shows that transport uncertainties result from uncertainties in the runoffs, currents, and salinities. Transports vary from 100,000 cubic meters per second in the Strait of Juan de Fuca to just 1500 cubic meters per second in Saratoga Passage, a fjord arm of Puget Sound. Where sufficient current measurements exist to estimate transports independently, the two techniques agree in general. Paradoxically, at the best sampled site off Point Jefferson near Seattle the mass conservation technique gives transports that are one-third to one-half of those estimated from midchannel current observations. The hypothesis is that at this site midchannel currents substantially overestimate the cross sectional mean because of the complex variation in the cross section of the along-channel current. This reduction in transport over previously estimated values means that the area of maximum refluxing, or recirculation, in Puget Sound is shifted south to a horizontally recirculating region around Vashon Island. The implications of this for the transport of contaminants is the subject of current research.

Plans FY 1988

LONG-RANGE-EFFECTS RESEARCH

- Continue the development of the laterally averaged model of Puget Sound.
- Include trace metal kinetics in the bottom boundary layer model.
- Conduct the Modeling Physical Oceanography Workshop of Puget Sound.
- Continue organizational efforts for Chapman conference on sediment transport in estuaries.
- Use the newly computed flux-weighted salinities and transports in Puget Sound to calculate the annual mean efflux/reflux coefficients and tracer concentrations and ages for inputs from a variety of sources.

- Begin laboratory studies on the rate of Pb scavenging onto hydrous manganese oxides.
- Continue laboratory adsorption studies on the effects of Cu complexation with dissolved organic matter.
- Complete a study of Kasten cores in Puget Sound comparing organic and trace metal profiles with ^{210}Pb dates.
- Begin identification of geochemically important organometallic compounds, particularly copper.

MARINE OBSERVATION AND PREDICTION

Research is directed toward understanding and improving the prediction of phenomena related to marine warning and forecasting services. Research subjects include sea-ice processes, arctic oceanography, vessel icing, and tsunami propagation and run-up. PMEL scientists work closely with colleagues at operational service components of NOAA such as the National Weather Service and the Navy/NOAA Joint Ice Center. Arctic research is also applicable to NOAA's climate studies. Research is carried out through a combination of field measurements, remote-sensing techniques, and numerical modeling.

Accomplishments FY 1987

ARCTIC RESEARCH

The Beaufort Sea Mesoscale Circulation Study

Three major field efforts were conducted: an icebreaker cruise in the Beaufort Sea in October 1986; a comprehensive helicopter-supported operation on the ice in the Beaufort Sea in March-April 1987; and a conventional cruise aboard the NOAA Ship *Surveyor* in the northern Bering, Chukchi, and Beaufort Seas in August-September 1987. The first year of this 2-year shelf circulation study has been aimed at (1) obtaining sufficient measurements of currents and various passive tracers to provide a primary description of the large-scale shelf circulation and its low-frequency variability; (2) determining the time-dependent wind forcing by extensive long-term automated measurements over the sea ice; and (3) investigating the seasonal hydrographic cycle in the Beaufort Sea, including that of nutrients and dissolved oxygen. Geochemical tracers sampled for other investigators included carbon-14, cesium, CFCs, strontium, and radium.

Sea-Ice Processes and Modeling

A coupled sea-ice, barotropic ocean model with a 1-km resolution and a seaward domain of 200 km has been developed to examine three coastal processes: coupling of ice motion to wind-driven coastal currents, thickness redistribution under compression at the coast, and the formation of coastal shear zones in the ice. Results of model calculations show that a new parameterization of ice strength is necessary for the coastal sea-ice problem. Analyses of ice drift from the vicinity of Bering Strait support this conclusion.

Investigations in the Greenland Sea

Studies in the Greenland Sea have two primary emphases: exchange processes with the Arctic Ocean through Fram Strait, and Greenland Sea circulation in the context of deep ocean ventilation. With respect to the first, substantial progress was made in analyses of both the west Spitsbergen and east Greenland currents. North of 79°N the west Spitsbergen current contains two separate warm cores that follow different isobaths. The western core, carried by the offshore branch of the current, follows the western flank of the Yermak Plateau, and north of 80°N at least part of this flow detaches from the plateau, probably contributing to the recirculation in Fram Strait. In contrast, the inshore branch follows the shelf break into the Arctic Ocean. During the transit of the inshore waters past northwestern Spitsbergen, the core properties change primarily through vertical heat flux, which during ice-free conditions in winter is estimated to be about 200 $W\ m^{-2}$ from the core layer alone. Together with some freshening within the Arctic Ocean, this process is responsible for fully transforming the original Atlantic water into arctic intermediate water within about 600 km of Fram Strait. With respect to the East Greenland current, long-term moored measurements near 79°N have shown that its mean southward transport above 700 m is about $3 \times 10^6\ m^3\ s^{-1}$ and has no obvious seasonal variability. About one-half of this transport appears to be barotropic. There is a rich mesoscale structure in the current records, much of which can be interpreted as trains of eddies and eddy-pairs with cross-stream length scales of about 10 km. Despite the abundance of eddies, turbulent heat fluxes are very small even in the vicinity of the polar front. Baroclinic instability is therefore not a major source of these eddies.

With respect to circulation of the Greenland Sea and its relationship to deep-ocean ventilation, an ice breaker cruise was conducted during June 1987, concentrating on the relatively unexplored western and southwestern Greenland Sea Basin. In addition to mooring work, a series of high-precision hydrographic sections was obtained, which substantially illuminated both the fate of the dense Arctic Ocean outflow in the Greenland Sea and the eastward recirculation of waters north of the Greenland-Jan Mayden Ridge.

TSUNAMIS

Tsunamis are unpredictable and often devastating sea waves produced by submarine earthquakes or volcanic eruptions. Almost 100 destructive tsunamis have occurred in the past century, killing more than 51,000 persons in coastal areas of the Pacific Basin. In the last 10 years alone, six tsunamis in the Pacific have claimed 5,646 lives. A critical problem has plagued tsunami research for decades: the nearly total lack of high-quality field measurements of tsunamis as they are generated, propagate across the deep ocean, and are amplified in shallow water near a coast. In 1986, PMEL initiated the Pacific Tsunami Observation Program (PACTOP) to address this problem. The initial tsunami monitoring network consisted of five deep-ocean bottom pressure recorders (BPRs) deployed at key locations on the ocean bottom. Four BPR sites were selected near the Aleutian trench since this region has been the source of three of the six major tsunamis that have impacted the U.S. coast since 1946; the fifth is about 250 miles offshore of the Oregon coast, along a probable tsunami propagation path to the U.S. mainland.

During FY 1987, all major PACTOP objectives were met: the development and fabrication of a new, more compact BPR design; recovery of all five units previously deployed; re-establishment of the monitoring network by deployment of replacement BPRs, including two of new design. In addition to meeting these major objectives, this project developed an important agreement with the U.S. Army Corps of Engineers during 1987, which effectively and inexpensively doubles the size of the PACTOP network and expands high-quality tsunami measurement coverage into the critical nearshore region of the U.S. west coast and Hawaii. Under this agreement, data collection procedures will be modified at nine stations of the more extensive coastal network maintained by the Corps of Engineers. Originally intended to collect swell, wind-wave, and storm surge data, these sites will now be capable of measuring tsunamis. Four of the gauges are in bays and harbors, and will monitor the response of these inlets to an incident tsunami; the remaining five instruments are at exposed coastal locations, and will thus provide valuable information on tsunami amplification due to shoaling.

The THRUST (Tsunami Hazard Reduction Using System Technology) project completed its goal to demonstrate the concept of a regional early warning system by coupling seismic instrumentation with state-of-the-art satellite communication technology. The design and 1-year testing of the necessary equipment were completed for instruments installed at Valparaiso, Chile. Simulations of the local shoreline response to tsunami energy were completed, and the results were incorporated into the early warning system's evacuation plan. The 1-year test revealed a 96% reliability for communications and equipment. The project exceeded design criteria for speed and reliability.

Plans FY 1988

ARCTIC RESEARCH

- Conduct a second year of helicopter operations on the ice in the Beaufort Sea during March-April 1988. At that time, moorings deployed in 1987 will be recovered.

- Conduct FREEZE project CTD observations in the Chukchi Sea during September and October. The project will relate the rate of the fall ice advance to the pre-existing heat content of the water column.

- Deploy five new moorings in the central Greenland Sea during June-July 1988 in a program coordinated with other research laboratories in Germany, Norway, and the United States. At the same time, recover the moorings deployed in the southwestern Greenland Sea during 1987.

- Participate in the intensive 1988-1989 volumetric census in the Greenland Sea, designed to quantify the winter water mass transformation and ventilation.

- Conduct arctic meteorology studies with emphasis on air-ice momentum and heat transfer through data analysis of previous aircraft experiments and modeling studies of the atmospheric boundary layer.

TSUNAMIS

- Recover and re-deploy all deep-ocean BPRs of the PACTOP network.

- Process all BPR records acquired in FY 1987, and perform analyses related to micro-tsunami detection, tidal dynamics, satellite altimeter sea-level estimates, and the nature of observed low-frequency pressure and temperature phenomena.

MARINE RESOURCES

Hydrothermal venting, which occurs along seafloor-spreading centers, represents a basic input of heat and materials into the oceans. The effect of hydrothermal venting on the marine environment is the focus of PMEL's marine resources program called VENTS. Research efforts have been specifically designed to define and quantify the chemical, geological, and physical oceanographic processes evolving from the venting of hydrothermal fluids.

The FY 1987 VENTS Program continued the systematic, quantitative study of the chemical and thermal effect of hydrothermal venting from the Gorda/Juan de Fuca/Explorer seafloor-spreading-center system. Seagoing research efforts were carried out aboard the *Discoverer*, the *Atlantis II*, and the submersible *Alvin*. Accompanying VENTS Program scientists from both PMEL and AOML were collaborating investigators from the United States Geological Survey, the Geological Survey of Canada, the Universities of Washington, Oregon State, Florida, Michigan, California, and Hawaii, the University of Victoria (Canada), and Woods Hole Oceanographic Institution.

PMEL's second major area of research in marine resources, Fisheries-Oceanography Coordinated Investigations (FOCI), began as a separately funded program in FY 1986. It is a joint effort by scientists at PMEL and the Northwest and Alaska Fisheries Center (NWAFC) to address the question of the recruitment variability of commercially valuable fish and shellfish stocks in the Gulf of Alaska and Bering Sea. The long-term goal is to establish environmental indices that can be monitored and interpreted to provide useful forecasts of recruitment.

Accomplishments FY 1987

VENTS PROGRAM

Juan de Fuca Ridge

Investigations of the southern Juan de Fuca Ridge focused on systematic hydrographic surveys to map the distribution of hydrothermal activity along the entire segment. Two notable discoveries were made. Most unusual and exciting was the discovery of "Megaplume," a brief but massive release of hydrothermal fluids from the northern end of the Southern Juan de Fuca Ridge. The heat output of the eruption, which apparently lasted for only a matter of days, was equal to the annual production of 200-2000 high-temperature black-smoker chimneys. The Megaplume may have been formed from a rifting event accompanied by a lava extrusion on the ridge axis.

In addition to Megaplume, the survey found extensive evidence for the existence of a very large "normal" vent field, also at the northern end of the segment. The size and intensity of the plume as defined by its temperature and particulate lead indicate that the vent field is much larger than

the only previously known field on this segment. The discovery of a large and chemically distinct field near the end of this segment puts important constraints on the development of theories concerning the distribution of heat sources along this and other spreading centers.

The axial vent field is an extensive (1000 m × 200 m) warm-water venting region characterized by orange amorphous silica deposits, extensive clam beds, and isolated vestimentiferan worm colonies. Within the vent field there are four major sulfide edifices, the tallest of which is about 5 m high. All are venting hot water; in many cases temperatures exceed 330°C. Fluids exiting the hottest vents appear to have exceeded critical pressure/temperature boundaries and contain disassociated fluid phases. Fluid temperatures have been determined to fluctuate by more than 40°C in some vents.

By virtue of these discoveries, it is clear that hydrothermal venting is more prevalent than previously held; that is, it occurs at locations along spreading centers other than along-axis bathymetric highs, and supplementing "normal" steady-state venting are bursts of episodic hydrothermal output that may ultimately be shown to be thermally and chemically at least as important as the former sources.

Data from 18 deep-tow camera surveys, both still and video photographic data from 15 *Pisces* submersible dives, and a series of deep-towed sidescan sonar surveys have been digitally processed into series of extremely detailed maps of the hydrothermal vent fields in the caldera of Axial Volcano. Well over 20,000 discrete photographic images from still and video coverage of the Axial's principal vent field were integrated into a digital data base.

A major objective of the VENTS Program is to quantitatively assess the effects of submarine venting from the entire Gorda/Juan de Fuca/Explorer seafloor-spreading center on the regional chemistry of the North Pacific ocean. During 1987, an extensive surface ship program was carried out aboard the *Discoverer* to map the distributions of hydrothermally derived Si, $^{3}He_{,,}$ Mn, Fe, CO_2, and heat up to 1500 km away from the spreading-center axis. Initial results have shown that hydrothermal emissions from the ridge form a 500-m-thick plume elongated in the direction of net current flow and centered on the 27.70 potential density surface. The integrated anomalies for Si and heat are thought to represent approximately 100 years of hydrothermal production along the entire ridge system.

A major significance of the Si-versus-heat results is that the observed anomalies are apparently related to hydrothermal sources along the northeast spreading-center system and that the sources of these chemical signals may vary dramatically from time to time in terms of volume and rate of output. A profile along the 47°N parallel shows a middle-depth (2100 m) Si anomaly that extends across the entire north Pacific and is segregated into centers of high and low concentrations. A major question to be addressed in light of the foregoing discussion and the Megaplume discovery is whether or not the high- versus low-Si anomalies are related to episodic hydrothermal output of the Gorda/Juan de Fuca/Explorer system.

Past field work at Axial Volcano has provided a large data set of SeaBeam bathymetry, Sea MARC sidescan sonar data, bottom photographs, and direct observations of the seafloor by means of submersibles. Techniques are being devised, through the use of spectral analysis and

fractal geometry, to quantify the surface roughness of the seafloor in specific areas, through the application of pattern recognition techniques to digital sidescan sonar images, and through development of analytical methods for inferring acoustic properties from SeaBeam echoes to reliably relate these remotely sensed acoustic data to direct observations of the seafloor. Such a capability will allow quantitative assessment of the extent and mode of occurrence of hydrothermal activity over large areas of the seafloor within realistic time and resource constraints.

By correlation of continuously sensed temperature data with discrete sample values for plume Mn, chemical flux data were successfully determined for the dispersing plume at the southern Juan de Fuca site. It was shown that the integrated flux for Mn, determined from the plume measurements, was higher than the estimates that would be projected from vent fluid measurements alone.

An initial assessment of the temporal and spatial variabilities of the plume chemistry associated with the hydrothermal vent field located at the southern end of the Juan de Fuca Ridge has been completed. In the 4 years during which the mid- to far-field chemical compositions of the plumes from this site have been sampled, they have remained invariant. At the same time, however, the proximal plume inventories from the active vents have waxed and waned.

Another important result at the Southern Juan de Fuca site was that during the past 4 years, distinct chemical signatures have been maintained at adjacent vents within the same field. These observations will help to place the hypothesis of ridge segment-moderated hydrothermal activity in perspective.

Geochemical evidence for scavenging by plume particulates of the oxy-anions P, V, Cr, and As from seawater was obtained. This is significant because it demonstrates a secondary effect of hydrothermal venting on the chemistry of seawater. For Cr, for example, the mass of metal scavenged per unit of plume water approaches the normal water concentration for that element in the northeast Pacific. The scavenging of the biologically critical nutrient phosphorous by hydrothermal particles has been estimated, on the basis of ridgeflank sediment data, to be equivalent to 15%-40% of the annual riverine input on a global scale.

By the end of the fiscal year, systematic geochemical studies of proximal plumes originating at venting orifices and extending through continuous space and time for kilometers and days of plume evolution and dispersal were accomplished through a unique coordination of surface ship and submersible sampling. As a part of the near-field observations, a prototype in-situ chemical monitoring system was deployed for the first time.

Numerical models of turbulent, buoyancy-driven plumes were created to assist the interpretation of data surrounding Megaplume. Such models propose that upward convection of the plume is forced by the buoyancy of the hot hydrothermal fluid with respect to the surrounding cold seawater. The buoyancy is diminished over distance from the source by entrainment of ambient water into the plume. Eventually density equilibrium in a stably stratified environment stops the rise of the plume. The height of the plume can be used to infer the value of heat flux from the vent.

Very little information is available at present concerning the middle-depth circulation around the Juan de Fuca ridge. Moreover, what is known does not appear to be consistent with larger-scale circulation patterns in the north Pacific. The first leg of the FY-1987 field season was dedicated to the deployment of an array of seven long-term current meter moorings positioned at distances extending to 150 km west of the southern portion of the Juan de Fuca seafloor-spreading center. Three moorings were also deployed on and immediately east and west of the ridge. In conjunction with deployment of the current meters, CTD observations were recorded extending from the surface to the seafloor along two lines extending 150 km westward from the ridge and separated by 50 km.

Technological Achievements - Submersible-Coupled Vent Fluid Sampling and Sensing System

During the FY-1987 field work with *Alvin*, a submersible-coupled instrument system specifically designed to sample and sense fluids discharging from submarine hydrothermal vents was used at the southwest vent field in the caldera of Axial Volcano. The system minimizes mixing of vent fluid and sea water during sampling, provides for the capture of relatively uncooled vent fluids in water- and gas-tight titanium samplers, and continually measures in situ temperature, conductivity, and light attenuation along the insulated flow path of the instrument. The data obtained with this system are significantly better constrained thermodynamically than those collected using the previously available vent fluid samplers. Later, the system will be adapted for use by the NOAA *Pisces* submersible in support of VENTS research in the northeast Pacific.

In-Situ Vent Chemistry Analysis System

During FY 1987, a prototype in situ chemical sensing system was constructed and deployed at a low temperature vent in the caldera of Axial Volcano. The scientific rationale for the system involves quantifying temporal variations known to occur in active vents. Such data make it possible to study the mass balance of materials as vent waters are injected into the water column. The in situ system simultaneously monitors variations in temperature, Fe, Mn, sulfide, and pH. Measurement of Fe, Mn, and sulfide is based on a relatively new analytical technique, flow-injection analysis.

FISHERIES-OCEANOGRAPHY COORDINATED INVESTIGATIONS (FOCI)

Alaskan Coastal Current

Current meter data from the Shelikof Strait sea valley clearly show that the Alaska Coastal Current (ACC), which flows through Shelikof Strait and across the continental shelf southwest of Kodiak Island, is a relatively narrow (about 20 km) filament whose position in the sea valley varies with time. Year-to-year changes in how larvae interact with this current may be more important than interannual changes in the magnitude of ACC transport. Transport in the sea valley appears to be highly geostrophic; the difference in bottom pressure across the sea valley accounted for the majority of transport fluctuations. The current meter data also confirm recent

findings from CTD data that there exists an estuarine-like flow in the sea valley. It was determined that the Shelikof pollock population is the principal pollock population in the Gulf of Alaska. Almost no larvae were found upstream in the Alaskan coastal current.

Drifter Studies

Eighteen satellite-tracked drifters were deployed during April and May 1987 in a line across Shelikof Strait from Cape Kekurnoi to Middle Cape. All were drogued at 45 meters where the highest concentration of pollock larvae are found. These drifter trajectories allowed examination of current fluctuations that influence transport of pollock larvae. The drifters traveled to the southwest from the deployment site and remained on the shelf for a minimum of 45 days, after which some entered the Alaskan Stream. Considerable horizontal variability was observed in the currents, and the influence of strong spring storms on the drifters was evident. By July, 13 drifters were still functioning; of these, 6 were in the the Alaskan Stream and the rest were aground on the Alaska Peninsula or nearby islands. Of the six drifters in the Alaskan Stream, five originated from the southern portion of the two arrays. After a transit time of 38 to 60 days, three drifters entered the Bering Sea through passes between the Aleutian Islands. These trajectories indicate that young pollock originating in Shelikof may enter the Bering Sea by this route.

Satellite Image Analysis

A basic processing and analysis system has been developed at PMEL to meet the needs of FOCI. This system includes image selection, geographical registration, flow vector generation, and graphics routines for color plots and video loops. Satellite images from a comprehensive 1987 data set have been selected and purchased, and research plans have been completed to integrate these data with in situ observations. Processing and analysis of selected April 1986 AVHRR images show that the Alaskan Coastal Current is marked by a strong, unstable front along its northern boundary. A large meander of the Alaska Stream, which flows south of Kodiak Island, removes water from the continental shelf near the Shelikof sea valley and returns it to the continental shelf approximately 100 km to the southwest. The mesoscale flow pattern shows a clockwise rotating elliptical eddy with a major axis of 50 km off Wide Bay, inshore of the major ACC flow from the Strait, with a perturbation sea-surface topographic relief of 10 cm. The spatial distributions in the images suggest that sub-mesoscale features as small as 15 km can evolve to dominate the local turbulent environment. This work is in collaboration with Texas A. & M. University.

FOCI Climatology

In support of FOCI a study has been initiated to develop and assess several indices describing the large-scale atmospheric circulation over the region. The purpose of this investigation is to provide three qualitatively different environmental indices characterizing the large-scale atmospheric forcing of the ocean circulation in Shelikof Strait region. These indices will be used to relate environmental conditions, particularly air-sea interactions, to the interannual variability in

walleye pollock. Calculation of the indices is being directed at the World Data Center-A for Glaciology at CIRES.

The cyclone frequency and surface winds indices have been completed, and several large-scale weather indices such as the north Pacific oscillation have been tested. Autocorrelation analysis of the time series of u and v wind components was performed with the intention of characterizing persistence in the different years. Low numbers of significant autocorrelation were observed in the u-wind for 1980, 1982, and 1985. Years exhibiting a high degree of autocorrelation in the calculated u-wind are 1981 and 1983. The high values indicate a high degree of persistence in the calculated winds, and the low values indicate the frequent passage of cyclonic storms. It was also determined that Pacific-basin-wide indices are less valuable to characterize weather variability for FOCI than single location indices, as in this study, because FOCI is interested in the weather during the transition month of April. Future analyses will include local steering-level winds and thermal indices.

Plans FY 1988

VENTS PROGRAM

- Conduct detailed geological and chemical surveys of the Megaplume site (Rift A) with *Alvin.*
- Determine the regional fluxes of Mn and Fe from Rift B Segment venting sites detected during FY-1987 surveys.
- Determine the degree of chemical diversity between Rift A and Rift B vents.
- Develop two-dimensional models for the fate of Fe and Mn from Rift A hydrothermal vents in the middle and far fields.
- Merge sidescan, water column, and photogeologic data into an integrated digital data set for analysis, interpretation, and compilation into detailed geological and hydrothermal-parameter maps.
- Conduct *Alvin* dives, particularly at the Megaplume site, for purposes of geological, chemical, and physical oceanographic surveys and sampling.
- Test and deploy second-generation instrumentation for vent fluid sampling and in situ chemical monitoring. The second-generation instruments will extend sensing capability to include high-temperature vents, thus providing a full-range chemical capability for monitoring long-term chemical vent behavior.
- Complete the detailed mapping of Axial Volcano (particularly the summit caldera) with *Alvin.* Incorporate FY-1987 sidescan sonar, photogeology, and geological and chemical sampling results.

- Initiate literature study of geological deformation associated with movement of magma in active terrestrial volcanoes as an analog, to similar behavior within the Axial Volcano caldera. Undertake second-generation experiments, using *Alvin* and instruments including bottom pressure recorders, to identify suitable sites for long-term measurement of crustal deformation versus hydrothermal variability.

- Continue the systematic study of the distribution of hydrothermal activity on the Juan de Fuca Ridge by making a hydrographic survey of the Northern Symmetrical Segment.

- Extend the regional assessment of proximal plume distributions and chemistries to include the Northern Symmetrical Segment.

- Compile and analyze existing camera, bathymetric, and sidescan sonar data to facilitate water column chemistry surveys.

- Locate and determine the strength of hydrothermal activity at northern Gorda Ridge.

- Continue to compare the geological and chemical characteristics of the northern Gorda Ridge hydrothermal vent environment with like data acquired through collaborative studies at Mid-Atlantic Ridge hydrothermal sites.

- Continue analysis of the statistics of patterns recorded in the digital sidescan sonar data and their correspondence to high-resolution seafloor photography as a means for both reconnaisance and detailed remote sensing surveys of potential hydrothermal sites.

- Prepare detailed maps and cross sections of the distributions of hydrothermally derived Si, Mn, Fe, and CO_2 throughout the northeast Pacific.

- Continue studies of the distributions of hydrothermal constituents in sediment cores recovered along the western rise of the Juan de Fuca Ridge.

FOCI

- Continue time series at four current meter sites and two wind stations and annual egg and larval sampling cruises.

- Obtain intensive measurements of food supply, predation, and mixing processes in an advecting larval patch.

- Synthesize information on current variability, particularly from the 1987 data set.

- Synthesize data on spatial distribution of eggs, larvae, and the zooplankton community in relation to hydrography and circulation.

- Develop a long-term (35-year) time series of a weather index for the region.

- Apply starvation/predation assessment methods to field samples of walleye pollock larvae.
- Begin theoretical investigation of current interaction with topography.

JIMAR

The Joint Institute for Marine and Atmospheric Research (JIMAR), located at the University of Hawaii, was formed in 1978, under a memorandum of understanding between NOAA and the University of Hawaii. The principal research interests of JIMAR are equatorial oceanography, climate, and tsunamis. A new emphasis on fisheries oceanography will begin in FY 1988.

During FY 1987, JIMAR scientists continued their active participation in many national and international research efforts.

Accomplishments FY 1987

CLIMATE RESEARCH

Studies on the effect of synoptic disturbances on the interannual variability of Pacific equatorial sea-surface temperature (SST) continued. This has involved a major effort to evaluate the Comprehensive Ocean-Atmosphere Data Set (COADS). Tropical Marine Climatic Atlases of SST, sea level pressure, surface wind, and surface stress, based on COADS data for 1900-1979 were published.

A study of surface pressure fluctuations in the tropical Pacific, using both island and ship data, is in progress. Two phenomena of interest are a westward-propagating pressure disturbance with periods of 4-5 days, and simultaneous pressure fluctuation on Pacific-basin-wide scales. Production of monthly mean surface wind and stress analyses using data from ships, islands, and low-level cloud motion, continues. These wind data sets are now being used by ocean modelers, and have given favorable results, compared with other available wind products.

A numerical model has been developed to study 30-60 day tropical variability in the atmosphere.

EQUATORIAL OCEANOGRAPHY

The Tropical Oceans and Global Atmosphere (TOGA) Sea Level Center continues to archive and study sea-level data. Studies of both interannual and intra-seasonal variability are being carried out. A major study was completed on inter-hemisphere differences in sea-level response during El Niño/Southern Oscillation (ENSO) events. An Indian Ocean sea-level network is being developed, and some stations are now operating.

Analysis of data from expeditions I and II of the Western Equatorial Pacific Ocean Circulation Study (WEPOCS) has continued. A working group on WEPOCS hydrographic data met in Hawaii in January 1987.

The third Line Islands Array Cruise took place in June 1987. Inverted echo sounders and subsurface pressure gauges were recovered and deployed. CTD stations were made on a line from Oahu to Malden Island.

Studies of deep equatorial zonal flows using Pegasus current-profiling data are continuing. Acoustic Doppler current profiler (ADCP) measurements were made in WEPOCS, on a Chinese vessel as part of the United States/People's Republic of China TOGA project, and on the University of Hawaii R/V *Moana Wave*.

In September 1987 two major meetings were held at JIMAR. The first was an Air-Sea Interaction Meeting, to plan a major observational program in the western Pacific as part of TOGA. The second was a meeting to recommend what observations the World Ocean Circulation Experiment (WOCE) should make in the tropical oceans.

TSUNAMI RESEARCH

We have continued our real-time tsunami observational capability in the Hawaiian Islands. Models have been developed to study the possible tsunami and excitation of harbor resonances, with application to the records from the May 1986 tsunami.

Plans FY 1988

CLIMATE RESEARCH

- A deep-water oceanographic station will be occupied monthly north of Oahu as part of WOCE.
- Model studies on the atmospheric 30-60 day oscillation will continue, with special attention to the role of instabilities and the distribution of heat sources.
- Studies of simultaneous basin-wide pressure fluctuations and interannual SST variability will continue.

EQUATORIAL OCEANOGRAPHY

- A third WEPOCS cruise to study the low-latitude western boundary current in the Pacific will be carried out in the spring of 1988.
- A fourth Line Islands Array cruise will be conducted in June 1988.
- Operation of the Pacific Sea Level Network and TOGA Sea Level Center, and installation of Indian Ocean sea-level gauges, will continue.

- Modeling studies on the effects of the coastal geometry of western boundaries will be extended to the Atlantic and Pacific Ocean cases.

TSUNAMI RESEARCH

- The real-time tsunami monitoring capability will be maintained.
- Numerical model studies on tsunami source mechanisms, using both shallow-water and three-dimensional codes, will be undertaken.
- A storm surge model for the Hawaiian island chain will be developed.

FISHERIES OCEANOGRAPHY

- In FY 1988 a visitor program on oceanography related to fisheries will be started. Particular areas of interest are the pelagic ecosystem in the North Pacific transition zone, recruitment patterns around tropical islands, tropical estuarine ecology, and the interaction of seamounts with ocean currents.

JISAO

The Joint Institute for the Study of the Atmosphere and Ocean (JISAO) was established in FY 1977 to foster collaboration between NOAA and the University of Washington. JISAO serves as a vehicle for funding grants and postdoctoral Fellows, supporting collaborative research efforts between NOAA and University scientists. During the past year, JISAO has emphasized three core research areas: climate, environmental chemistry, and estuaries.

JISAO's climate research focused on two main themes: large-scale atmosphere-ocean interaction in the tropics and planetary-scale wave/mean flow interaction. The main research focus of Environmental Chemistry have been the carbon dioxide problem and chemical processes involving the deposition of heavy metals. The former focus is closely related to certain aspects of the climate research in JISAO, and the latter to the estuarine research. Research on global environmental chemistry has broadened in scope to include other biogeochemical cycles of interest for global climate. Of particular interest is the chemistry of sulfur and its influence on cloud condensation nuclei and the cycles that involve long-lived radiatively interactive trace species such as nitrous oxide and methane.

During the past year JISAO has explored the possibility of developing a program to study global climate change and establishing a Center for Climate Modeling. Studies at such a Center would complement research envisioned at a proposed (University-based) NOAA-funded Experimental Climate Forecast Center.

Accomplishments FY 1987

Coupled ocean-atmosphere models relevant to the El Niño/Southern Oscillation phenomenon in the equatorial Pacific were developed. They range in complexity from the simple physical models to the more complete Cane and Zebiak (1987) model. The latter model displays oscillations that somewhat resemble the observed Southern Oscillation. A linearized version of the Cane and Zebiak model was used to show that linear model behavior is similar to that of the full, nonlinear model; the main effect of nonlinearities is to limit the growth of the oscillation. The gross behavior of the linear model could be explained by a very simple model involving a local positive feedback in the central eastern Pacific interacting with a time-lagged negative feedback resulting from mid-ocean generation of Rossby waves and their subsequent reflection at the western oceanic boundary.

Studies were carried out regarding comparative diagnostics of low-frequency variability of the Oregon State University General Circulation Model and observations and forecast sensitivity experiments with the NCAR Community Climate Model.

Work was completed on the comparison of the tropospheric stationary wave pattern forced by localized vorticity sources in two-layer and continuously stratified models of linear quasi-geostrophic theory. In general, the two-layer model gives a good representation of the stationary wave-train and its dependence on damping parameters. An exception is the serious distortion that may occur when two-layer shears are baroclinically stable. Extensive numerical experiments have also been conducted in an attempt to isolate the quasi-geostrophic regime that supports persistent spatially organized storm-tracks.

Work is continuing under NSF sponsorship to study the response of the equatorial Pacific and Indian Oceans to the annual cycle in atmospheric forcing.

JISAO Senior Fellows and Fellows, and JISAO-affiliated students and institute scientists participated in a PMEL-sponsored conference, "Global Climate Prediction on the Scales of 10-100 Years." JISAO participated in and helped sponsor the campus-wide Environmental Chemistry Day, "Global Chemistry." JISAO has continued an active role in facilitating collaboration and interaction among environmental chemists working in several departments on the University campus. JISAO also hosted the October 1986 meeting of the NAS/US TOGA Panel.

Numerous research projects are funded through JISAO; these include development of instrumentation for monitoring chemical fluxes from hydrothermal vents, studies of acid-base chemistry of marine air and the role of the ocean in producing DMS and NH^3, the relationship between extratropical sea-surface temperature (SST) anomalies over the North Pacific and wintertime climate anomalies over North America, and numerical experiments to model the radiance distributions over the oceans.

Plans FY 1988

- Expand the effort to address scientific issues associated with global climate change. This will include an attempt to establish a climate-modeling capability that could serve as a focus for research on coupled atmosphere/ocean interaction and biogeochemical cycles.
- Begin a program of exploratory field measurements of atmospheric and marine sulfur.
- Continue a vigorous visitor and seminar program.
- Host the August 1987 meeting of the NAS/U.S. TOGA Panel.

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PMEL SEMINARS

Dates	*Name and Affiliation*	*Seminar Topic*
1986		
20 September	Dr. J. Sarmiento NOAA/GFDL	CO_2 and circulation in the ocean
	Dr. V. Ramanathan University of Chicago	Introduction and overview: the greenhouse problem
21 October	Dr. John Roads Scripps Institution of Oceanography University of California	Long range prediction
7 November	Dr. Phyllis J. Stabeno Department of Oceanography Oregon State University	Deep sea currents off northern California
17 November	Prof. Arne Foldvik Geophysical Institute University of Bergen Norway	Mechanisms for bottom water formation in the Weddell Sea
9 December	Pierre Mourad Department of Atmospheric Sciences University of Washington	Nonlinear resonant interaction: theory and application to large eddies in a neutral atmospheric boundary layer
15 December	Dr. Cho-Teng Liu Institute of Oceanography National Taiwan University Taipei, Taiwan	The Kuroshio near Taiwan
1987		
2 March	Dr. Brian Atwater US Geological Survey Seattle, Washington	Tsunamis from great northwest earthquakes over the last 5000 years

17 March	Dr. Stan Hayes Dr. Michael McPhaden NOAA/PMEL	The El Niño of 1987?
21 April	Dr. Eli Katz Lamont-Doherty Geological Observatory Columbia University	The use of inverted echo sounders in oceanography
19 May	Prof. Brian Farrell Harvard University	Physically based parameterizations for simple climate models
3 June	Dr. Don Scavia NOAA/GLERL	From picoplankton to fish: complex interactions in Lake Michigan
28 July	Dr. Kensuke Takeuchi Hokkaido University Japan	Equatorial waves relating to onsets and terminations of Los Niños in the Hokkaido University model
7 August	Dr. Mark Luther Florida State University	Modeling the seasonal and interannual variability in the Indian Ocean
11 August	Dr. William L. Landing Florida State University	Methods for investigating the oceanic biogeochemistry of manganese and iron

JISAO SEMINARS

Date	*Name and Affiliation*	*Seminar Topic*
1986		
7 August	Dr. Harry Hendon Division of Atmospheric Research Aspendale, Victoria, Australia	On the structure and dynamics of the troposphere over the CSIRO Indonesian region
25 August	Dr. Marie Farge Laboratoire de Meteorologie Dynamique du C.N.R.S. Ecole Polytechnique Paliseau, France	Inertia-gravity wave effects on a decaying two-dimensional turbulence in rotation
18 September	Dr. Jerry Mahlman NOAA/GFDL Princeton University	High resolution modeling of the middle atmosphere
31 October	Dr. Akimasa Sumi Geophysical Institute Tokyo University Japan	Equilibrium states over the tropical ocean with zonally uniform SST surrounded by the dry continents
21-22 October	Dr. John Roads Scripps Institution of Oceanography University of California	Long range prediction Predictability and extended range prediction
29 October	Dr. Jurgen Willebrand Visiting Professor Germany	The role of salinity in a large-scale ocean circulation
7 November	Dr. Anthony Hirst JISAO	Slow instabilities in a tropical ocean basin-global atmosphere model

13 November	Dr. J.M. Wallace and Visiting Scholar Dr. Quan-rong Jiang Nanjing University People's Republic of China	The role of extratropical SST anomalies in climate variability
17 November	Dr. Hisanori Itoh UCLA	The generation mechanism of mixed Rossby-gravity waves in the equatorial troposphere
1987		
8 January	Dr. David Gutzler AER	Low frequency wind fluctuations over the tropical western Pacific
29 January to 2 February	Claude Kergomard Laboratory of Atmospheric Physics University of Lille France	AVHRR data for sea-ice studies Features of a marginal ice zone in Fram Strait from AVHRR-MIXEZ 1984K
25 February	Dr. Jurgen Willebrand Visiting Professor Germany	Some technical aspects of ocean circulation modeling
26 February	Dr. Michael Ghil UCLA	The 30-50 day oscillation in the global atmosphere observations, laboratory experiments and theory
27 February	Dr. Yoshi-Yuki Hayashi University of Tokyo Japan	Hierarchy structure in the equatorial atmospheric circulation
1 April	Dr. Antonio Speranza Dinamica Atmosferica-Fisbat Bologna, Italy	Statistical properties of the general circulation
2-3 April	Dr. Steven L. Mullen Department of Atmospheric and Oceanic Sciences University of Michigan	Transient eddy forcing blocking flows Explosive cyclogenesis in a global spectral model

9 April	Dr. Theodore V. Blanc Atmospheric Physics Branch Naval Research Laboratory Washington, D.C.	An error analysis of the bulk method determined fluxes used in air-sea interaction modeling and remote sensing
21-22 April	Dr. Eli Katz Lamont-Doherty Geological Observatory Columbia University	The use of inverted echo sounders in oceanography Pressure gradients in the Atlantic during SEQUAL
12 May	Ramone Mujica University of Piura Peru	Scientific collaboration with JISAO director and students
19-22 May	Dr. Brian Farrell Harvard University	Physical based parameterizations for simple climate models Cyclogenesis - the initial value perspective Optimal excitation of neutral Rossby waves
19-28 May	Dr. Byron Boville NCAR University of Colorado	Four lectures on numerical modeling of the general circulation, including: Numerical modeling of the general circulation, Part III; Numerical modeling of the general circulation, Part IV
26 May	Dr. Leonid Brevdo UCLA	Absolute and convective instabilities in stratified flows
29 May	Dr. Byron Boville NCAR University of Colorado	Trace gas influences on climate

JIMAR SEMINARS

Date	*Name and Affiliation*	*Seminar Topic*
1986		
29 September	Mr. Jeff Proehl University of Washington	Equatorial wave-mean flow interaction: the long Rossby wave
10 October	Dr. Mark A. Lander Department of Meteorology University of Hawaii	Large-scale changes of the wind, sea-level pressure, and clouds associated with cross-equatorial twin cyclones in the equatorial western Pacific
20 October	Dr. John Allen College of Oceanography Oregon State University	Quasi-geostrophic topographically generated mean flow over the continental margin
17 November	Dr. Catherine Gautier California Space Institute Scripps Institution of Oceanography	Precipitation patterns and the monsoon in 1979 - results of the 40-50 day oscillation
18 November	Dr. Catherine Gautier California Space Institute Scripps Institution of Oceanography	Oceanography and climatology from space
19 November	Dr. Stephen Chiswell Graduate School of Oceanography University of Rhode Island	Equatorially-trapped waves at 85° and 95°W during the 1982-83 El Niño
21 November	Dr. David Anderson Department of Atmospheric Physics Clarendon Laboratory University of Oxford	Data assimilation for TOGA
17 December	Dr. Cho-Teng Liu Graduate School of Oceanography National Taiwan University Taiwan	The Kuroshio Current near Taiwan

1987

6 January	Dr. Zygmunt Kowalik Institute of Marine Science University of Alaska	Modeling of the tsunami from the Shumagin Gap
22 January	Dr. Mitsuhiro Kawase Department of Earth, Atmospheric, and Planetary Sciences MIT	Establishment of mass-driven abyssal circulation
9 July	Dr. Eddie Bernard PMEL/NOAA	Scientific programs of the Pacific Marine Environmental Laboratory
31 July	Mr. William Kessler Department of Oceanography University of Washington	Ocean GCM hindcasts of the 1982-83 El Niño
8 August	Dr. Frank Chew NOAA/AOML	Type-B meandering in the Florida Strait
27 August	Dr. Jurgen Sundermann Institute für Meereskünde University of Hamburg West Germany	Model simulation of tides in the Asian-Australian waters

PMEL PUBLICATIONS

AAGAARD, K., A. Foldvik, and S.R. Hillman. The West Spitsbergen Current: Disposition and water mass transformation. *Journal of Geophysical Research* 92(C4):3778-3784 (1987).

Recent work suggests that the West Spitsbergen Current, which provides the principal contribution to the Arctic Ocean of salt and sensible heat, as well as of a variety of anthropogenic tracers, is a rather complex circulation feature. North of 79°N, where the isobaths diverge markedly, the current contains two separate warm cores that follow different isobaths. The western core, carried by the offshore branch of the current, follows the western flank of the Yermak Plateau, and north of 80°N at least part of this flow detaches from the plateau, probably to contribute to the recirculation in Fram Strait. In contrast, the inshore branch follows the shelf break into the Arctic Ocean. It is this inshore branch that provides the primary focus in this paper. During the transit of the inshore waters past northwestern Spitsbergen, the core properties change primarily through vertical heat flux, which during ice-free conditions in winter is estimated to be of the order of 200 W m^{-2} from the core layer alone. Together with some freshening within the Arctic Ocean, this process is responsible for fully transforming the original Atlantic water into arctic intermediate water within about 600 km of Fram Strait.

AAGAARD, K., and R. REED. Fram Strait: Exchange and dynamics. *Eos, Transactions of the American Geophysical Union* 69(9):124-125 (1987).

During November 18-20, 1986, a workshop entitled "Fram Strait: Exchange and Dynamics" was held at the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory in Seattle, Wash. A total of 27 talks were presented, and approximately 50 scientists attended. The principal issues addressed were the role of exchanges through Fram Strait in the regional and large-scale circulation and geochemical cycling and the factors driving and controlling flow through the strait. Fram Strait, between Greenland and Spitsbergen, is the deep passage between the Arctic Ocean and the North Atlantic extension in the Norwegian and Greenland seas (Figure 1). Although much of the discussion dealt with the strait proper, many aspects of the Arctic Ocean and its adjacent seas were also treated, as were some aspects of straits in general. For purposes of convenience, we report on the meeting in terms of four major topics: circulation and hydrography, chemical tracers, models, and ice and boundary layers. We also briefly describe the proposed Greenland Sea Project. While some of the presentations are not easily and neatly pigeonholed into the four topical categories, we have listed the speakers according to their primary emphasis.

AAGAARD, K., S. SALO, and K. Krogslund. Beaufort Sea mesoscale circulation study: Hydrography, USCGC Polar Star Cruise, October, 1986. NOAA DR ERL PMEL-19 (NTIS not yet available), 83 pp. (1987).

No abstract.

Abbott, D.H., M.A. Hobart, and R.W. EMBLEY. Heat flow and mass wasting in the Wilmington Canyon Region: U.S. Continental Margin. *Geo-Marine Letters* 6:131-138 (1986).

The average corrected heat flow in the Wilmington Canyon region, an area of inferred slope instability, is 35 ± 10 mW/m^2. This average heat flow is marginally consistent with the 46 ± 9 mW/m^2 measured at other North Atlantic sites over 160 m.y. old. High topographic relief causes most of the variability in surface heat flow and may lower the mean surface heat flow. There is no significant difference between the average corrected heat flow of 35 ± 10 mW/m^2 in sediment slide areas and the average corrected heat flow of 34 ± 10 mW/m^2 in undisturbed sediments.

Acker, J.G., R.H. Byrne, S. Ben-Yaakov, R.A. FEELY, and P.R. Betzer. The effect of pressure on aragonite dissolution rates in seawater. *Geochimica et Cosmochimica Acta* 51(8):2171-2175 (1987).

Aragonite dissolution in seawater at variable pressure is well described by the equation

$$\text{Rate} = \kappa'([CO_3^{2-}]_s - [CO_3^{2-}])^n$$

where $[CO_3^{2-}]_s$ is the carbonate ion concentration at saturation, $[CO_3^{2-}]$ is the observed carbonate ion concentration, and κ' and n are empirical constants. Application of the equation

$$\text{Rate} = \kappa(1 - \Omega)^n$$

to descriptions of aragonite dissolution rates (where $\Omega = [CO_3^{2-}]/CO_3^{2-}]_s$ is appropriate at constant pressure, temperature and salinity. Our measurements in seawater at 5°C are consistent with the estimate $-\Delta V = 36.5$ cm^3/mole for the volume change accompanying aragonite dissolution. This result is somewhat higher than laboratory estimates, but lower than estimates based on calcite and difference between calcite and aragonite molar volumes.

Bailey, K., R. Francis, and J.D. SCHUMACHER. Recent information on the causes of variability in recruitment of Alaska pollock in the Eastern Bering Sea: physical conditions and biological interactions. Proceedings of the International North Pacific Fisheries Commission, Bulletin #47, 155-165 (1986).

No abstract.

BAKER, E.T., and G.J. MASSOTH. Characteristics of hydrothermal plumes from two vent fields on the Juan de Fuca Ridge, northeast Pacific Ocean. *Earth and Planetary Science Letters* 85:59-73 (1987).

Deep CTD/transmissometer tows and water bottle sampling were used during 1985 to map the regional distribution of the neutrally-buoyant plumes emanating from each of two major vent fields on the Southern Symmetrical Segment (SSS) and Endeavour Segment (ES) of the Juan de Fuca Ridge. At both vent fields, emissions from point and diffuse hydrothermal sources coalesced into a single 200-m-thick plume elongated in the direction of current flow and with characteristic temperature anomalies of 0.02-0.05°C and light-attenuation anomalies of 0.01-0.08 m^{-1} (10-80 $\mu g/\ell$ above background). Temperature anomalies in the core of each plume were uniform as far downcurrent as the plumes were mapped (10-15 km). Downcurrent light-attenuation trends were non-uniform and differed between plumes, apparently because different vent fluid chemistries at each field cause significant differences in the settling characteristics of the hydrothermal precipitates. Vent fluids from the SSS are metal-dominated and mostly precipitate very fine-grained hydrous Fe-oxides that remain suspended in the plume. Vent fluids from the ES are sulfur-dominated and precipitate a high proportion of coarser-grained Fe-sulfides that rapidly settle from the plume. The integrated flux of each vent field was estimated from measurements of the advective transport of each plume. Heat flux was 1700 ± 1100 MW from the ES and 580 ± 351 MW from the SSS. Particle flux varied from 546 ± 312 g/s to 204 ± 116 g/s at the ES depending on distance from the vent field, and was 92 ± 48 g/s from the SSS.

BAKER, E.T., and G.J. MASSOTH. Hydrothermal plume measurements: a regional perspective. *Science* 234:980-982 (1987).

An extensive deep-two survey around an active submarine vent field was conducted to map the three-dimensional distribution of hydrothermal emissions and calculate the hydrothermal discharge of heat and manganese. Emissions from the 10-kilometer-long vent field formed a nearly isopycnal plume about 250 meters thick and elongated in the direction of the local net current. Net export of hydrothermal discharge from both point and diffuse sources was estimated from the advective transport of the plume; the heat flux was $5.8 \pm 2.9 \times 10^8$ watts and the dissolved manganese flux was 0.2 ± 0.1 moles per second. Flux measurements of this type could be expanded to encompass entire ridge segments, allowing comparison with theoretical thermal and chemical process models on a common spatial scale.

BAKER, E.T., G.J. MASSOTH, R.W. Collier, J.H. Trefrey, D. Kadko, T.A. NELSEN, P.A. RONA, and J.E. Lupton. Evidence for high-temperature hydrothermal venting on the Gorda Ridge, northeast Pacific Ocean. *Deep-Sea Research* 34(8):1461-1476 (1987).

The first water-column survey of the axial valley of the Gorda Ridge, a slow- to medium-rate spreading center within 300 km of the coast of Oregon and California, found strong evidence for ongoing hydrothermal venting. At the northern end of the ridge, anomalously high concentrations of helium-3, dissolved manganese, particulate iron, and methane confirmed the hydrothermal origin of above-bottom plumes identifiable as maxima in light-attenuation profiles. The presence of excess radon-222 and the highly soluble hydrothermal precipitate anhydrite in the plumes require a local vent source; the precipitation of anhydrite requires fluid temperatures of at least 130°C. Indications of hydrothermal activity elsewhere in the axial valley were inconclusive.

BAKER, E.T., G.J. MASSOTH, and R.A. FEELY. Cataclysmic hydrothermal venting on the Juan de Fuca Ridge. *Nature* 329:149-151 (1987).

Serial observations of individual submarine hydrothermal vents and the mapping of dilute hydrothermal plumes extending far downcurrent from vent fields indicate a stability of vent field fluid composition and mass flux on at least decadal time scales. The inherent episodicity of ridge-crest tectonic activity, however, suggests that discontinuous emissions of hydrothermal fluids also occurs. In support of this hypothesis we report here the discovery of a 700-m-thick, 20-km-diameter eddy-like "megaplume" created by a brief but massive release of high-temperature hydrothermal fluids near 44°49'N, 130°140'W on the Juan de Fuca Ridge. The megaplume had a mean temperature anomaly of 0.12°C and overlay compositionally distinct plumes emanating from an apparently steady-state vent field at the same location. The megaplume was formed in a few days yet equalled the annual output of between 200 and 2,000 high-temperature chimneys.

BATES, T.S., R.J. Charlson, and R.H. GAMMON. Evidence for the climatic role of marine biogenic sulphur. *Nature* 329:319-321 (1987).

Oceanic dimethylsulphide (DMS) emissions and atmospheric aerosol particle populations (condensation nuclei, CN), resolved by latitude and season, appear to be directly correlated, in that CN, as measured with a condensation nucleus counter, are high (or low) in regions where DMS fluxes and incident solar radiation are high (or low). Although it has been previously hypothesized that CN are produced from DMS, we report the first attempt to correlate DMS flux and CN. As the population of cloud condensation nuclei (CCN) in marine air is a subset of the CN population, and CCN in turn control the albedo of marine clouds, DMS could be involved in climate control through a cloud albedo feedback mechanism.

BATES, T.S., J.D. Cline, R.H. GAMMON, and S.R. KELLY-HANSEN. Regional and seasonal variations in the flux of oceanic dimethylsulfide to the atmosphere. *Journal of Geophysical Research* 92(C3):2930-2938 (1987).

Dimethylsulfide (DMS) concentrations have been measured in over 1000 Pacific surface seawater samples during the past 4 years. The data have been tabulated to take into account both regional and seasonal variations in concentration. The area-weighted summer and winter concentrations of DMS in the North Pacific Ocean are 2.2 and 1.3 nmol/L, respectively. Wind speed, surface seawater temperature, and DMS diffusivities are used to calculate air-sea exchange coefficients. The area-weighted summer and winter DMS piston velocities are 2.3 and 2.7 m/d, respectively. These exchange coefficients combined with the concentration data yield a net ocean to atmosphere DMS flux in the North Pacific Ocean of 0.12 Tmol/yr. Extrapolating this calculation by regional areas to the global ocean yields a net DMS flux of 0.50 Tmol/yr, less than earlier estimates of 1.2 Tmol/yr, but still consistent with excess sulfate deposition estimates and model studies of the marine atmospheric sulfur budget. The uncertainty in the flux estimate is roughly a factor of 2.

BATES, T.S., P.P. MURPHY, H.C. CURL, JR., and R.A. FEELY. Hydrocarbon distributions and transport in an urban estuary. *Environmental Science and Technology* 21(2):193-198 (1987).

Aliphatic and polycyclic aromatic (PAH) hydrocarbons were quantified on suspended particulates and surficial bottom sediments from the main basin of Puget Sound, WA. Total four-, five-, and six-ring PAH concentrations ranged from 0.6 to 3.2 μg/g dry weight of sediment. Concentrations of total n-alkanes and the unresolved complex mixture ranged from 3 to 35 and from 35 to 1100 μg/g, respectively. The highest hydrocarbon concentrations on particulates were found in the surface waters near Seattle. Concentrations decreased with depth in the water column and with distance from Seattle. Hydrocarbon distributions and concentration gradients show vertical flux as the major transport process. Although the hydrocarbon residence time in the water column is too short to horizontally mix the compounds, resuspension and lateral transport in the bottom nepheloid layer disperse the hydrocarbons through the fine-grained sediments in the center of the basin.

Bernstein, R.E., P.R. Betzer, R.A. FEELY, R.H. Byrne, M.F. LAMB, A.F. Michaels. Acantharian fluxes and strontium to chlorinity ratios in the North Pacific Ocean. *Science* 237:1490-1494 (1987).

Data on particulate strontium sulfate fluxes and strontium to chlorinity ratios were compared to provide insights into the strontium cycle of the North Pacific. Free-drifting sediment traps were used to derive large particle fluxes between depths of 100 and 3500 meters in the eastern and western North Pacific Ocean. Flux data revealed substantial quantities of acantharian skeletons and cysts (both made of strontium sulfate) settling through the upper kilometer of the water column. The greatest fluxes of celestite were detected at 400 meters. Minimal to nondetectable fluxes noted at and below 900 meters provide evidence that by this horizon, the majority of acantharian specimens had dissolved, thereby contributing to the

pool of dissolved strontium. Growth and subsequent dissolution of acantharians in the upper kilometer are qualitatively consistent with the well-developed minimum and maximum strontium to chlorinity ratios that are consistently noted in these waters. These fluxes of particulate strontium and model calculations for fluxes of dissolved strontium indicate that acantharians play an important role in the ocean's strontium budget.

Chen, C.T., M.R. Rodman, C.L. Wei, E.J. Olsen, R.A. FEELY, and J.F. GENDRON. Carbonate chemistry of the North Pacific Ocean. DOE Technical Report TR034, DOE/NBB-0079, 176 pp. (1986).

Data collected by us along two longitudinal cruises serve as the main data sources, and supplementary data sets in the literature are selected for delineating the distribution of physical and chemical properties in a wide area of the North Pacific Ocean. Oxygen, pH, alkalinity, total CO_2, and nutrients are interrelated parameters. Along our two longitudinal sections they all show a core structure underlying the salinity minimum layer. From these oxidation-related parameters we conclude that the subsurface water of the eastern North Pacific Ocean is older than that of the western North Pacific Ocean. Alkalinity data can be used as a water mass tracer. Different water masses reveal their own mixing trends which can be identified when we examine the correlation of normalized alkalinity with temperature. The vertical distribution of the normalized alkalinity shows a maximum core at a depth of about 2500 m in the North Pacific Ocean. Calcium carbonate dissolution and circulation in the deep and bottom layers contribute to the formation of the normalized alkalinity maximum core. Our calcium and alkalinity data indicate a $CaCO_3$ dissolution rate of 0.060 and 0.053 μmol/kg/yr, respectively, referenced to the Weddell Sea Deep Water for waters deeper than 2000 m. The organic carbon decomposition rate is 0.107 μmol/kg/yr and the oxygen consumption rate is 0.13 μmol/kg/yr, also for waters below 2000 m. Our analysis of carbonate data shows that about 25% of the increase in total inorganic CO_2 in deep water, in its journey from the surface of the Southern Ocean to the depth of the North Pacific, results from inorganic $CaCO_3$ dissolution. No significant difference in the inorganic carbon/organic carbon ratio exists between our two sections. We found, however, that the eastern section has a higher total TCO_2 input than that of the western section. The degree of saturation with respect to calcite and aragonite was calculated from all available data sets. Four selected cross-sections, three longitudinal and one latitudinal, and two three-dimensional graphs show that a large volume of the North Pacific is undersaturated with respect to $CaCO_3$. The saturation horizon generally shows a shoaling from west to east and from south to north in the North Pacific Ocean. It was found that the lysocline falls at a depth much deeper (about 2500 m deeper) than the saturation horizon of calcite and several hundred meters shallower than the calcium carbonate compensation depth. Our results appear to support the kinetic point of view on the $CaCO_3$ dissolution mechanisms. Our calculations on the excess CO_2 show that its penetration depth is strongly related to circulation. The shallowest penetration depth is less than 300 m found in the eastern equatorial region where upwelling prevails an the deepest penetration depth is deeper than 2000 m off Japan where an interaction of Oyashio and Kuroshio currents is found. These results agree with conclusions drawn based on freons, tritium and carbon-14 data. Overall the North Pacific contains $14.7 \pm 4 \times 10^{15}$ g excess carbon.

CURL, H.C., JR., E.T. BAKER, T.S. BATES, G.A. CANNON, R.A. FEELY, T.L. GEISELMAN, P.P. MURPHY, D.J. PASHINSKI, A.J. PAULSON, M.F. ROBERTS, and D.A. TENNANT. Contaminant transport from Elliott and Commencement Bays - Final Report to EPA, August 1987, 269 pp. (1987).

No abstract.

EMBLEY, R.W., and R. Jacobi. Mass wasting in the western North Atlantic. In *The Geology of North America*, Vol. M, The Western North Atlantic Region, P.R. Vogt and B.E. Tucholke (eds.). Geological Society of America, 479-490 (1986).

No abstract.

FEELY, R.A., R.H. GAMMON, B.A. TAFT, P.E. PULLEN, L.S. WATERMAN, T.J. CONWAY, J.F. GENDRON, and D.P. WISEGARVER. Distribution of chemical tracers in the Eastern Equatorial Pacific during and after the 1982-1983 El Niño/Southern Oscillation event. *Journal of Geophysical Research* 92(C6):6545-6558 (1987).

During April 1983 and March-April 1984, two cruises were conducted in the central equatorial Pacific to determine the effects of the El Niño/Southern Oscillation (ENSO) event on the sea-air exchange of CO_2. Measurements of total carbon dioxide, pCO_2, total alkalinity, freon-11, salinity, temperature, oxygen, nutrients, and wind and current velocities were made along three meridional transects (158°W, April 1983; 150°W, March 1984; 170°W, April 1984). The cessation of upwelling during the ENSO event caused pCO_2 concentrations in surface waters to decrease to near-saturation levels along the equator. The calculated net flux of CO_2 across the sea-air interface was essentially negligible in the eastern equatorial Pacific during this period. However, when normal trade winds and consequent upwelling returned in late 1983 and early 1984, the equatorial region returned to a pCO_2 condition of highly supersaturated surface waters in the region between 8°N and 8°S along the 150° and 170°W transects. The calculated post-ENSO sea-air flux of CO_2 exceeded 6.0 mmol CO_2 m^{-2} d^{-1}. The mean annual CO_2 flux in the equatorial Pacific was estimated to be 0.02 Gt of carbon during the 1982-1983 ENSO event as compared with 0.6 Gt during 1984.

FOX, C.G. An inverse Fourier transform algorithm for generating random signals of a specified spectral form. *Computers and Geosciences* 13(4):369-374 (1987).

A simple FORTRAN algorithm which produces a random signal of a specified length and spectral form is presented. Such artificially generated signals are useful in modeling natural phenomena, calibrating other algorithms, comparing signals of measured observational or laboratory data, or providing multiple realizations of a given statistical process. Because of the prevalence of power-law form spectra in nature and its relationship to fractal forms, the algorithm provides a convenient manner of generating profiles of a given fractal dimension.

The routine is modified easily for generating signals of any specified spectral form, and several such forms are illustrated.

FREITAG, H.P., M.J. MCPHADEN, and A.J. SHEPHERD. Equatorial current and temperature data: 108°W to 110°W; October 1979 to November 1983. NOAA DR ERL PMEL-17 (PB87-204004), 99 pp. (1987).

No abstract.

GAMMON, R.H., W.D. KOMHYR, and J.T. Peterson. The Global Atmospheric CO_2 Distribution 1968-1983: Interpretation of the results of the NOAA/GMCC measurement program. In *The Changing Carbon Cycle: A Global Analysis*, J.R. Trabalka and D.E. Reichle (eds.), Springer-Verlag, New York, 1-16 (1986).

The modern period of precise atmospheric CO_2 measurements began with Keeling's pioneering determinations at Mauna Loa, Hawaii, and the South Pole during the International Geophysical Year. The Mauna Loa record (e.g., Keeling 1983) remains the single most valuable CO_2 time series for carbon cycle model verification. For very recent interpretations of atmospheric CO_2 measurements and carbon cycle relationships, the reader is referred to Cleveland *et al.* (1983), Keeling (1983), Machta (1983), Mook *et al.* (1983), Pearman *et al.* (1983), Keeling *et al.* (1984), Wong *et al.* (1984), Bacastow *et al.* (1985), Komhyr *et al.* (1985), and Fraser *et al.* (this volume). In this chapter, the global atmospheric CO_2 records, particularly of the NOAA/GMCC (National Oceanic and Atmospheric Administration/ Geophysical Monitoring for Climatic Change) program, are summarized for the period 1968 through 1983, with emphasis on the mean properties of the global carbon cycle as viewed from the atmosphere (i.e., global mean CO_2 concentration, latitude dependence of concentration and seasonal amplitude, airborne fraction, etc.).

GILLETTE, D., W.D. KOMHYR, L.S. WATERMAN, D. STEELE, and R.H. GAMMON. The NOAA/GMCC continuous CO_2 record at the South Pole, 1975-1982. *Journal of Geophysical Research* 92(D4):4231-4240 (1987).

Hourly carbon dioxide concentrations at the south pole were obtained by nondispersive infrared analyzers for the years 1975-1978 and 1980-1982. A spectral analysis of the ambient CO_2 variability showed very little power for periods shorter than 5 days. Our data showed good agreement with other data sets for the range of the annual fluctuation from 1977 to 1982 and disagreements for 1976. The estimated annual CO_2 increase (about 0.6 to 2 ppm yr^{-1}) and ranges of seasonal fluctuation were insensitive to the data selection methods used. After 1979, seasonal fluctuations apparently decreased.

GONZALEZ, F.I., E.N. BERNARD, and H.B. MILBURN. A program to acquire deep ocean tsunami measurements in the North Pacific. Proceedings, Coastal Zone '87, WW Div., ASCE, May 26-29, 1987, Seattle, WA, 3373-3381 (1987).

Deep ocean tsunami measurements are needed to provide open ocean boundary conditions for testing numerical models in hindcast studies, and for improving our understanding of tsunami generation and propagation. Jacob (1984) has identified a portion of the Aleutian Trench which includes the Shumagin Island group as a seismic gap (the Shumagin Gap); he has computed estimates which indicate that the probability of a great earthquake occurrence ($M_W > 7.8$) is significantly higher for this region than any other in the U.S. Because tsunamigenic earthquakes along a major portion of the seismically active Aleutian trench threaten Hawaii and the U.S. west coast, and because a large tsunami is possible in the event of a great earthquake in the Shumagin Gap, this region has become the focus of a long-term monitoring program by the Pacific Marine Environmental Laboratory (PMEL) of the National Oceanic and Atmospheric Administration (NOAA).

GONZALEZ, F.I., B.M. Holt, and G.D. Tilley. The age and source of ocean swell observed in Hurricane Josephine. *Johns Hopkins APL Technical Digest* 8(1):94-99 (1987).

The SIR-B mission has yielded expectionally valuable swell observations in the far field of Hurricane Josephine. This article applies a very simple kinematic model to provide estimates of the swell origin in space and time.

Hamann, I., and B.A. TAFT. On the Kuroshio extension near the Emperor Seamounts. *Journal of Geophysical Research* 92(C4):3827-3839 (1987).

In June-July 1982 and November 1983, studies were carried out of the vertical structure of the Kuroshio Extension along 167°E and the path of the current as it approached the Emperor Seamount chain; in addition, records from moored current meters at three locations (two at 167°E and one in the Main Gap of the Emperor Seamount chain) were obtained. The Kuroshio Extension in both 1982 and 1983 turned cyclonically (meander wave length of 450 km) as it approached the chain; the axis of the surface current was located in deep water (>3.5 km) in 1982 and in relatively shallow water (0.5 km) in 1983. In 1982 the horizontal temperature gradient decreased and the density surfaces down to 2000 m ascended as the Kuroshio Extension flowed over the Emperor Seamounts. In neither year was there evidence of current splitting as it crossed the seamounts. In 1983, in contrast to 1982, there was no weakening of the horizontal temperature gradient, and the Kuroshio Extension went over a very shallow portion of Kinmei Seamount (<500 m). The current measurements made at the time of the hydrographic section show that the instantaneous Kuroshio extended to the bottom (abyssal eastward current of 2 cm s^{-1}). The deep low-frequency eddy kinetic energy values are intermediate between those measured at 152°E and those at 158°W, suggesting a large-scale eastward decrease in deep eddy activity. Zonal mean flow near 3500 m at 167°E was essentially zero (0.1 cm s^{-1}); the mean meridional components were larger (-2.1 and -0.7 cm s^{-1}). At the southern side of the gap the deep flow was unusually steady ($K_E/K_M < 1$)

and directed northeastward into the eastern basin of the North Pacific; low ratios (O(1)) were also observed in the lower thermocline compared with those at 167°E (O(10-100)). The frequency content of the gap kinetic energy differed from that measured at 167°E: the highest frequency band (2 hours < P < 2 days) was the most energetic, whereas at 167°E the mesoscale band (20 days < P < 150 days) was the most energetic. The flow in the gap resembles in many of its characteristics that observed in two other channel flows: the Vema Channel and the Charlie Gibbs Fracture Zone.

Hampton, M.A., P.R. Carlson, H.J. Lee, and R.A. FEELY. Geomorphology, sediment and sedimentary processes. In *The Gulf of Alaska: Physical Environment and Biological Resources*, D.W. Hood and S.T. Zimmerman (eds.), DOC/NOAA, DOI, 93-143 (1986).

The Gulf of Alaska continental margin, from Cross Sound in the east to Chirikof Island in the west, has been shaped directly and indirectly by the forces of ice, plate tectonics, and ocean currents. Grounded ice extended to the shelf break at least once during the Pleistocene epoch, covering most or all of the shelf and sculpting broad flat banks and elongated troughs. Glacial, glacial-marine, and glacial-fluvial sediment was deposited in nearly all areas as the ice advanced. As the climate warmed and the ice retreated, the region was inundated by the sea, giving rise to the present geologic environments. The high, youthful mountains to the north of the Gulf provide a plentiful source of sediment that is delivered to the coastline by a few large rivers and remnant glaciers. The major input of sediment occurs in the northeastern Gulf (Copper River, Alsek River, Bering Glacier, and Malaspina Glacier sources) and at the head of Cook Inlet (Knik, Matanuska, and Susitna River sources). Ocean currents in the northeastern Gulf carry the sediment predominantly to the west, depositing much of the load near the shore and in the troughs but delivering some sediment into Prince William Sound and Shelikof Strait. Large embayments in the eastern Gulf coastline accumulate thick, underconsolidated deposits of sediment delivered by local high-gradient streams and glaciers. The coarse sediment from the rivers at the head of Cook Inlet is deposited near the points of entry and, along with the relict glacial sediment in the remainder of the Inlet, is reworked by strong tidal currents. As a result, fields of large sand waves and other current-related bed forms have developed. The fine sediment from the rivers is transported south down the Inlet and is deposited as a progressively sorted sediment blanket throughout Shelikof Strait. The Kodiak Shelf receives little modern sediment, but ocean currents rework the relict glacial debris, leaving coarse-grained lag deposits on the shallow banks and winnowed, fine-grained sediment in the troughs. Collision between the North American and Pacific lithospheric plates generates strong tectonic forces throughout the region. Over long durations of geologic time, these forces cause changes in seafloor elevation that create deep sedimentary basins and uplifted banks and islands. In the short term, strong and frequent earthquakes trigger submarine sediment slides in the deposits of soft sediment on the northeastern Gulf shelf and along the entire upper continental slope.

HAYES, S.P. The circulation of the equatorial Pacific Ocean. In *Further Progress in Equatorial Oceanography, a report of the U.S. TOGA Workshop on the Dynamics of the Equatorial Oceans*, E.J. Katz and J.M. Witte (eds.), Honolulu, HI, August 11-15, 1986, 145-164 (1987).

No abstract.

HAYES, S.P., L.J. MANGUM, R.T. Barber, A. Huyer, and R.L. Smith. Hydrographic variability west of the Galápagos Islands during the 1982-83 El Niño. *Progress in Oceanography* 17:137-162 (1986).

Nine hydrographic (temperature, salinity, and in some cases oxygen) and four zonal velocity sections near the equator along 95°W in 1980-1984 are presented and discussed. Perturbations associated with the 1982-83 El Niño form the focus for the discussion. This event was sampled by sections in November 1982 and in March, May, November and December 1983. The upper ocean response in November 1982 was a downward displacement of isotherms above 400 m on the equator. The Equatorial Undercurrent (EUC) was deep and strong for this season. The vertical displacement perturbations extended to at least 5°S and were more uniform with depth off the equator. In May 1983 the largest vertical displacements were observed. The EUC was replaced by a westward jet at about 75 m and the Equatorial 13°C Water thermostad had disappeared. Local estimates of the zonal pressure gradient suggest that between 110°W and 95°W this slope had reversed in May 1983 and was, at least in part, responsible for the observed westward jet. Local winds were westerly and forced the observed eastward surface current. By November 1983, surface conditions were fairly normal. However, the deeper stratification remained anomalous; the Equatorial 13°C Water thermostad was still missing. The vertical profile of vertical displacements from a mean suggested a complicated vertical structure near the equator. In April 1984 conditions had returned to near normal.

INCZE, L.S., J. GRAY, J.D. SCHUMACHER, A.W. Kendall, K.M. Bailey, and S.A. MACKLIN. Fisheries-Oceanography Coordinated Investigations (FOCI) Field Operations — 1986. NOAA DR ERL PMEL-20 (NTIS not yet available), 64 pp. (1987).

No abstract.

Kessler, W.S., and B.A. TAFT. Dynamic heights and zonal geostrophic transports in the central tropical Pacific during 1979-84. *Journal of Physical Oceanography* 17(1):97-122 (1987).

Dynamic height is calculated from XBT and surface salinity data in the central Pacific using a mean temperature-salinity (T-S) relation in the usual way below the thermocline but assuming isohaline water in the upper layer where the temperatures are isothermal. This scheme produces a better estimate of dynamic height than the use of a mean T-S relationship alone and produces significant improvements near the equator where small pressure gradients

imply large geostrophic currents. During the El Niño of 1982-83, water of very low surface salinity was observed spanning the equator; this event is attributed both to extreme local rainfall and anomalous advection from the western Pacific. Geostrophic transports of the major surface currents are estimated for the period January 1979 through December 1984. The North and South Equatorial countercurrents are found to have the largest annual fluctuations, and the vertical displacements of the thermocline associated with these fluctuations are qualitatively consistent with local Ekman pumping. A striking anomaly of the 1982-83 El Niño was a strong peak in North Equatorial Countercurrent transport in late 1982; at this time surface flow was eastward from 10°N to 5°S with volume transport on the order of $60\text{-}70 \times 10^6$ m^3 s^{-1}. In mid-1983 NECC transport fell to less than 2×10^6 m^3 s^{-1}. During the first four months of 1983 strong westerlies extended from the equator to about 10°S over a broad region in the central Pacific. The wind curl pattern associated with this anomaly led to shoaling of the thermocline by 60 m from 5° to 15°S.

LAVELLE, J.W., and W.R. Davis. Measurements of benthic sediment erodibility in Puget Sound, Washington. NOAA TM ERL PMEL-72 (PB87-208450), 32 pp. (1987).

Rates of erosion of bottom sediment were studied at seven locations in Puget Sound, Washington. Fresh, unremoulded sediment from box cores was exposed to turbulence in a fluid chamber in which turbulence is generated by oscillating a perforated disk at controlled frequencies. Resulting time series of particulate concentration in the chamber at each stepped level of equivalent bottom stress were used to calculate estimates of erosion rates and deposition velocities. Resulting rates of erosion at 1 dyne/cm^2 do not appear to be consonant with rates at higher stress, suggesting that a thin surficial layer of sediment is more easily eroded than sediment below. Differences of erosion rates among sites at stresses of 2 dynes/cm^2 and above are not resolvable with the available data.

LAVELLE, J.W., and H.O. MOFJELD. Bibliography on sediment threshold velocity. *Journal of Hydraulic Engineering* 113(3):389-393 (1987).

No abstract.

LAVELLE, J.W., and H.O. MOFJELD. Do critical stresses for incipient motion and erosion really exist? *Journal of Hydraulic Engineering* 113(3):370-385 (1987).

The concept of critical stress for the initial motion of noncohesive sediment beds under turbulent flow conditions is reviewed. Observational definitions of incipient motion are many and not entirely compatible. Some laboratory flume observations of sediment movement suggest that no true threshold exists. Current understanding of turbulent fluid motion at a sediment bed suggests that some particle movement must occur at all nonzero time-mean velocities. A combined model for flume flow and sediment transport having no threshold is seen to explain features of data that have been previously used to support the threshold concept.

MACKLIN, S.A. Coastal winds of the southeast Alaska Peninsula. NOAA TM ERL PMEL-73 (PB87-206173), 131 pp. (1987).

Hourly measurements of wind speed and wind direction from Cherni Island, Thin Point, Cold Bay, and Ugaiushak Island during the latter half of 1984 and the first half of 1985 show evidence of orographic steering of winds in the coastal zone. Surface wind directions at Cherni Island, Thin Point, and Cold Bay often were attributable - 30% of the time at Cherni Island and Thin Point, 50% of the time at Cold Bay - to channeling of the wind by a gap in the Aleutian Range. At Ugaiushak Island 30% of surface winds came from the WNW. It is likely that these winds followed a convoluted path through the mountains from the Meshik River valley to the southwest. Representations of topographically undisturbed surface winds for the same four locations over the period June 1984 through May 1985 were produced by turning and reducing gradient winds computed from digitized, 6-hourly, sea-level-pressure analyses obtained from the U.S. Navy's Fleet Numerical Oceanography Center. These wind estimates show a more evenly distributed wind direction population, with a slight tendency for winds to dominate from the NW and SE. Monthly correlation coefficients between measured and estimated u and v wind components ranged from 0.48 to 0.94. Because of anomalous winter and spring weather conditions, measured Cold Bay wind statistics for some months of the study do not compare favorably with climate averages. Yearly averages compare more favorably, and these statistics may be representative of normal conditions.

MACKLIN, S.A., N.I. JENKINS, and A.T. ROACH. Upper air observations in the vicinity of Shelikof Strait during the Fishery Oceanography Experiment (FOX), March 1985. NOAA DR ERL PMEL-16 (PB87-196408), 51 pp. (1986).

No abstract.

MANGUM, L.J., J.M. LYNCH, and S.P. HAYES. CTD/O_2 measurements during 1984 and 1985 as part of the Equatorial Pacific Ocean Climate Studies (EPOCS). NOAA DR ERL PMEL-18 (PB88-102082), 341 pp. (1987).

During 1984 and 1985, CTD data were collected in the eastern equatorial Pacific as part of the Equatorial Pacific Ocean Climate Studies (EPOCS) program, which began its field program in 1979. Summaries of CTD data from four cruises in 1984 and 1985 are presented. Station locations, meteorological conditions and profiles of temperature, salinity, sigma-T, and oxygen are shown for each cast. Additionally, T-S diagrams and section plots along 110°W, 140°W, and the equator are presented.

MAYER, D.A., and J.C. LARSEN. Tidal transport in the Florida Current and its relationship to tidal heights and cable voltages. *Journal of Physical Oceanography* 16:2199-2202 (1986).

A linear relationship between tidal height (sea level of tidal frequencies) and tidal transport near 27°N in the Straits of Florida is confirmed. Transport estimates from this relationship

for the O_1 and M_2 constituents are compared with those computed from cable voltages across the Florida Current. These estimates are independent in that the weighted tidal height model (tidal-height transport relationship) was developed using collective sets of current meter and velocity profiler data obtained at different times of the year and in different locations. The cable voltages, however, were calibrated using a quasi-synoptic sectional integration of depth-averaged profiler data. Further, a means is suggested by which changes in the cable calibration can be detected.

MCPHADEN, M.J. The Equatorial Undercurrent: 100 years of discovery. *Eos, Transactions of the American Geophysical Union* 67:762-765 (1986).

The Equatorial Undercurrent is a narrow ribbon of eastward flow centered on the equator in the upper thermocline. It is a permanent feature of the general circulation in the Atlantic and Pacific oceans and is present in the Indian Ocean in northern winter and spring during the northeast monsoon. It reaches speeds of 50-100 cm s^{-1} below the westward flow of the South Equatorial Current, and in the Pacific transports as much mass on average (40×10^6 m^3 s^{-1}) as the Florida Current, which feeds the Gulf Stream. The first observations of the Equatorial Undercurrent were made 100 years ago in 1886 by the Scotsman John Young Buchanan in the Gulf of Guinea. These observations were soon forgotten, however, and nearly 70 years were to pass before observations of the Pacific Undercurrent by Townsend Cromwell and Raymond Montgomery inspired more comprehensive ocean surveys and dynamical theories of equatorial circulation. This article reviews the chronology of historical events surrounding the multiple discoveries of the Equatorial Undercurrent and summarizes our present understanding of its dynamics.

MCPHADEN, M.J., and A.E. Gill. Topographic scattering of equatorial Kelvin waves. *Journal of Physical Oceanography* 17(1):82-96 (1987).

We develop a linear, reduced-gravity model with two active layers above a deep, resting layer to examine the scattering of equatorial Kelvin waves from meridional submarine ridges. Model ridges, idealized as infinitely long in the meridional direction and infinitesimally thin in the zonal direction, completely obstruct flow in the lower active layer. The equatorial long-wave approximation is made, which restricts the class of motions considered to nondispersive Kelvin and Rossby waves in each of two internal modes. Thus, coastal and topographically trapped phenomena are filtered out, but variability far from the ridge is accurately modeled. The scattering of Kelvin wave energy depends on two parameters, $r = H_0/H_1$ and $\gamma = (\rho_1-\rho_0)/(\rho_2-\rho_1)$, where H_0 and H_1 are the equilibrium thicknesses of the upper and lower active layers, respectively, and $\rho_0 \leq \rho_1 \leq \rho_2$ are the layer densities. Incident first internal mode Kelvin waves are little affected by a deep ridge (i.e., for large r) and strongly reflected by a shallow ridge (i.e., for small r). Second internal mode Kelvin waves behave in an opposite sense, being more strongly reflected by a deep ridge for example. Strong stratification typical of the tropics, corresponding to large γ, decouples the near surface from the deep ocean, enhancing the transmissivity of the first mode and the reflectivity of the second mode. Potentially observable topographic effects in the wake of low-

mode Kelvin fronts include enhanced eddying in the far field west of ridges, enhanced vertical shear of zonal flows over and east of ridges, and changes in the depth and intensity of the thermocline across ridges. Weak eddying may also be generated to the east of ridges in the form of boundary trapped currents.

MCPHADEN, M.J., J.A. Proehl, and L.M. Rothstein. On the structure of low frequency equatorial waves. *Journal of Physical Oceanography* 17:1555-1559 (1987).

We examine the effects of realistically sheared mean currents on low baroclinic mode equatorial Kelvin and Rossby waves. Mean flows can induce significant small scale zonal velocity fluctuations near the surface, can reduce pressure variations near the surface relative to those at depth, and can shift zero crossings by 0(100 m). Thus the vertical structure of dynamical modes is different than that given by the traditional modal decomposition for waves in a resting ocean.

Meyers, G., J.R. Donguy, and R.K. REED. Evaporative cooling of the western equatorial Pacific Ocean by anomalous winds. *Nature* 323(6088):523-526 (1986).

Global climate anomalies during El Niño/Southern Oscillation (ENSO) episodes are controlled by anomalous patterns of sea surface temperature (SST) in the equatorial Pacific Ocean. Many studies during the past decade have indicated that warming of the eastern Pacific is caused by advection and downwelling associated with anomalous eastward currents. Cooling of the western Pacific is probably not caused by an analogous process because zonal temperature gradients are small west of the dateline. We have searched for an explanation of the cooling because relatively small temperature changes in the west can be important in influencing the atmospheric general circulation. Here we compare oceanic heat storage observed by expendable bathythermographs during 1979-83 with local processes in the heat budget, including various surface fluxes and mixing. The results show that cooling during 1982-83 was caused by evaporation due to anomalous meridional wind. The anomalous wind field in the region had been noted earlier by Harrison.

MOBLEY, C.D., and R.W. PREISENDORFER. Reply. *Journal of Physical Oceanography* 17(4):551 (1987).

No abstract.

OVERLAND, J.E., C.H. PEASE, R.W. PREISENDORFER, and A.L. Comiskey. An algorithm for prediction of vessel icing. Proceedings, International Workshop on Winds and Icing, Halifax, Nova Scotia, October 7-11, 1985, 248-256 (1986).

An important meteorological variable for operations in high latitudes is the rate of accumulation of ice on vessels and structures. A set of 85 icing observations were collected for

Alaskan waters from intermediate size vessels (20-75 m) during 1979 to 1984, which were verified by interviews of the vessel operators and by comparison with National Weather Service analyses. Of the set of 85, 58 were open-ocean observations where the vessel was not heading down-wind; 25% of the reduced set had icing rates in excess of 2.0 cm/hr. An algorithm has been developed for relating vessel potential icing rate to a simplified predictor which considers wind speed, fetch, and air and sea temperatures. The new algorithm predicts icing rates greater than three times those of most previous icing nomograms.

OVERLAND, J.E., C.H. PEASE, R.W. PREISENDORFER, and A.L. Comiskey. Prediction of vessel icing. *Journal of Climate and Applied Meteorology* 25(12):1793-1806 (1986).

Vessel icing from wave-generated spray is a severe hazard to expanded marine operations in high latitudes. Hardships in making observations during operations, combined with differences in vessel type and heading, have resulted in great variability in vessel icing observations for similar meteorological conditions. This has led to difficulties in development of quantitative forecast procedures. A categorical algorithm for relating vessel icing potential to wind speed, and air and sea temperatures is presented which seeks to minimize these difficulties. A set of 85 icing observations were collected for Alaskan waters from intermediate size vessels (20-75 m) during 1979 to 1983, and verified by interviews with the vessel operators and by comparison with National Weather Service analyses. Of the set of 85, 58 cases were open-ocean observations where the vessel was not heading downwind; 25% of this reduced set had icing rates in excess of 2.0 cm h^{-1}. Icing rate nomenclature and predicted icing rates for a given set of meteorological parameters developed from this study, and recommended for operations, are similar to those developed by Soviet and Japanese authors, but are five times greater than those based on the classic study by Mertins. This disparity is probably related more to differences in data analysis than to real geographic differences in icing conditions.

OVERLAND, J.E., and A.T. ROACH. Northward flow in the Bering and Chukchi Seas. *Journal of Geophysical Research* 92(C7):7097-7105 (1987).

The ocean circulation on the Bering and Chukchi sea shelves is investigated using a barotropic numerical model. In the presence of the winter seasonal wind stress from the northeast, observed northward transport through Bering Strait of 0.6 Sv for the 8-month winter season 1981-1982 can be driven by a sea level difference of 0.4 m between the Pacific and Arctic oceans. This sea level difference between basins is in agreement with hydrographic estimates. In the absence of wind stress a 0.4-m sea level difference drives a northward transport through Bering Strait of 1.1 Sv. Maximum transport through Bering Strait is geostrophically limited, not frictionally or inertially limited. Major qualitative circulation features of the region are evident in the simulations. Westward intensification of the northward transport across the Bering Sea shelf is confirmed, with the major transport occurring in the relatively deep Gulf of Anadyr. In the absence of wind, Anadyr Strait contributes 72% of the northward transport through Bering Strait. With northeasterly winds there is a net clockwise circulation around Saint Lawrence Island. Within the 20-m isobath,

North and Kotzebue sounds are little influenced by the general circulation. Northward transport in the Chukchi Sea bifurcates in the vicinity of Point Hope. The predominant branch is directed toward the northwest in a broad canyon feature south of Heralds Shoal, and the balance becomes the Alaskan Coastal Current between Cape Lisburne and Point Barrow.

PEASE, C.H. The size of wind-driven coastal polynyas. *Journal of Geophysical Research* 92(C7):7049-7059 (1987).

The sizes of wind-generated coastal polynyas have been observed to be nearly constant for steady atmospheric conditions owing to the balance between the advection of sea ice away from the coast and the area-averaged production rate of new ice. A simple model is used to explore the relationship of several environmental parameters to the maximum size attained by the polynya and the speed at which the maximum is reached for a given atmospheric event. The model results suggest that size is strongly a function of air temperature, such that colder air produces a smaller polynya for a given offshore wind velocity. However, size is only moderately a function of wind speed, especially for winds greater than 10 m s^{-1}, since increasing the speed increases both the advection rate and the ice production rate. The model results are compared to observations made around a coastal polynya during February 1982 and 1983 along the southern coast of St. Lawrence Island in the northern Bering Sea and during February 1985 along the southern coast of the Seward Peninsula. The model correctly predicts the general maximum dimensions of these winter polynyas, although the atmospheric stationarity assumptions limit the usefulness of the predictions of the speed at which the maximum is reached. The results of this study suggest that the contribution of heat from the coastal ocean to the high-latitude winter atmosphere is a self-limiting process proportional to the amount of time the wind-driven ice drift has a component normal to the coast. This has important implications for the interpretation of satellite imagery for ice-covered oceans and for understanding high-latitude climate dynamics.

PEASE, C.H. Meteorology of the Chukchi Sea: an overview. Chapter 3 in *Chukchi Sea Information Update, June 1987*, D.A. Hale (ed.), NOAA/NOS/OCSEAP, DOI, 11-19 (1987).

No abstract.

PEASE, C.H., and S.A. SALO. Sea ice drift near Bering Strait during 1982. *Journal of Geophysical Research* 92(C7):7107-7126 (1987).

Six Argos ice stations were deployed in the northeastern Bering Sea in January and February 1982. Four moved north through Bering Strait and made between one and five passes through the strait before they sank or were crushed by the ice, and two remained in western Norton Sound and Shpanberg Strait. Net winds in the region were directed toward the southwest and were relatively uniform geographically. Net currents were northward, and both mean velocity and mean speed were greater at Bering Strait than at Shpanberg Strait. Norton Sound contributed ice northward through Bering Strait in the mean during winter and

spring. There was also a net divergence of ice near Cape Lisburne. A theory for open-shelf shallow water ice drift is developed that adds terms for bottom drag and stress feedback from the water column. A stress analysis for a station that remained in western Norton Sound and Shpanberg Strait showed that bottom drag did not contribute significantly but that stress feedback from the accelerated shallow water current can be of the same order as the Coriolis force. However, the analysis contained a residual, possibly associated with internal ice stress, coastal setup, or unknown measurement error, which was of roughly the same order as the wind and current stress.

PETERSON, J.T., W.D. KOMHYR, L.S. WATERMAN, R.H. GAMMON, K.W. THONING, and T.J. CONWAY. Atmospheric CO_2 variations at Barrow, Alaska, 1973-1982. *Journal of Atmospheric Chemistry* 4:491-510 (1986).

The first 10 years (1973-1982) of atmospheric CO_2 measurements at Barrow, Alaska, by the NOAA/GMCC program are described. The paper updates and extends the Barrow CO_2 record presented in *Tellus* (1982). The data are given in final form, based on recent calibrations of the Scripps Institution of Oceanography, with selected values identified as representative of large, space-scale conditions. Analyses of the data show: (1) a long-term CO_2 average increase of 1.3 ppm per year, but with large year-to-year variations in that growth rate; (2) a suggestion, not statistically significant, of a secular increase in the amplitude of the annual cycle, presumably a reflection of global-scale biospheric variability; and (3) good absolute agreement between the Barrow results and those from four neighboring high latitude sites between 50 and 82°N.

PREISENDORFER, R.W. Theory of fluorescent irradiance fields in lakes and seas. NOAA TM ERL PMEL-70 (PB87-196465), 249 pp. (1987).

It is shown how to determine the irradiance field in lakes and seas that have fluorescing stratified layers of chlorophyll and other organic material. This is the direct solution of the irradiance field which starts from the depth-distribution of optical properties, in particular the spectral absorption and scattering functions of the material. Conversely, it is shown how to determine these optical properties, from irradiance probe measurements in situ, by inverting the direct solutions for the irradiance field. The present work forms the basis for applications of radiative transfer theory to remote sensing of seas and lakes and specifically for optically-based chlorophyll assays within such media. In particular, it is shown how to determine the intrinsic (or specific) optical properties of a natural hydrosol from irradiance measurements in the hydrosol.

PREISENDORFER, R.W., C.D. MOBLEY, and T.P. Barnett. The principal discriminant method of prediction: Theory and evaluation. NOAA TM ERL PMEL-71 (PB87-209276), 76 pp. (1987).

The Principal Discriminant Method (PDM) of prediction employs a novel combination of

principal component analysis and statistical discriminant analysis. Discriminant analysis is based on the construction of discrete category subsets of predictor values in a multidimensional predictor space. A category subset contains those predictor values which give rise to a predictand (or observation) in that particular category. A new predictor value is then assigned to a particular category (i.e., a forecast is made) through the use of probability distribution functions which have been fitted to the category subsets. The PDM uses principal component analysis to define the multidimensional probability distribution functions associated with the category subsets. Because of its underlying discriminant nature, the PDM is also applicable to problems in data classification. After presenting the theory of the PDM, it is subjected to four analyses. The first uses actual data to forecast discrete values of horizontal visibility over the ocean, using the PDM in a Model Output Statistics (MOS) setting. The second analysis is also in an MOS setting, but this time artificially constructed data sets are used, with predetermined levels of noise and inherent predicability. In each study the PDM is compared with other forecast methods (such as linear regression). The third analysis uses the PDM to forecast the onset of the 1982-83 El Niño, as expressed by sea surface temperature anomalies, using wind anomalies as the predictors. In the fourth analysis, sea level pressures over the North Pacific are used to predict surface air temperatures over North America. It is found that when applied to artificial data, the PDM shows forecast skills which are comparable to other standard forecast techniques. However, when applied to actual data sets, the PDM is generally outperformed by other forecast techniques. It is concluded that the failure of the PDM in these situations is a consequence of the noisy nature of the data sets, which prevents the PDM from adequately defining the category subsets. If the input data sets are suitably smoothed or filtered in order to increase the signal-to-noise ratio, then the PDM is once again comparable in skill to other forecast techniques. The underlying concepts of the PDM do, therefore, appear sound, and it is felt that the PDM shows considerable promise.

Proehl, J.A., M.J. MCPHADEN, and L.M. Rothstein. A numerical approach to equatorial oceanic wave-mean flow interactions. In *Advanced Physical Oceanographic Numerical Modelling*, J.J. O'Brien (ed.), 111-126 (1986).

An efficient numerical method is employed to investigate the interaction of equatorial trapped waves with vertically and meridionally sheared zonal jets. The model is formulated with the Equatorial Undercurrent in mind but has general applicability. The governing differential equation is derived and expanded using central differences into finite difference form. The linear system of equations leads to a coefficient matrix of block-tridiagonal form which is efficiently solved using a direct method. The direct method involves an optimized Gauss elimination and backsubstitution. For long Kelvin waves in the absence of mean flow, the analytic solution is obtained numerically with a high degree of accuracy. A diagnostic test is derived for use in cases where the analytic solution is unknown. The model is then applied to situations in which waves are superimposed on a background flow containing a critical surface where the flow speed matches the phase speed of the wave. For these cases, the waves are damped and absorbed in a frictional layer surrounding the critical surface. For speeds characteristic of the Undercurrent, all but the first few baroclinic Kelvin modes

encounter critical surfaces which may prevent the establishment of higher baroclinic modes in the equatorial ocean.

PULLEN, P.E., Bernstein, R.L., D. Halpern. Equatorial long-wave characteristics determined from satellite sea surface temperature and in situ data. *Journal of Geophysical Research* 92(C1):742-748 (1987).

Sea surface temperature (SST) maps and imagery derived from the NOAA 6 satellite Advanced Very High Resolution Radiometer (AVHRR) for June and July 1981 in the eastern tropical Pacific portray the wavelike structure of the cool water along the equator from 93°W to 125°W. Cusped waves of approximately 1000-km zonal wavelength and 25-day period propagated westward with a phase speed of 40 km/day. The observed meridional extent between the crest and trough of the waves is about 300 km. Details in the imagery show cooler water at the cusps advected north and then east with the north equatorial countercurrent (NECC), consistent with the suggestion of a series of anticyclonic eddies occupying the shear zone between the NECC and the westward flowing south equatorial current. Absolute SST estimates from the AVHRR data agree to within 0.6°C with shipboard data taken along 110°W between 5°N and 5°S. The wavelike structures in the SST maps are also in agreement at the surface with a vertical expendable bathythermograph temperature section made along the equator between 93°W and 125°W, which shows the phase of the waves tilting westward with increasing depth over the upper 75 m. Such a phase shift, if it extended 100-200 km meridionally in either direction from the equator, would be associated with an equatorward flux of heat. Similar phase shifts appear in temperature time series at depths of 20 and 50 m, from a mooring at 0°33'N, 110°30'W. Near-surface currents measured at this and a second mooring on the equator at 109°40'W indicate a regular pattern of northward advection when wave cusps pass them, followed by southwest flow during the passage of wave troughs, again consistent with an equatorward flux of heat, as well as with earlier theoretical and drift buoy findings.

REED, R.K. Salinity characteristics and flow of the Alaska Coastal Current. *Continental Shelf Research* 7(6):573-576 (1987).

Data from three sections in the central and western regions of the Alaska Coastal Current, obtained during a 10-day period in autumn 1981, are used to derive indices of salinity structure coherent with density gradients and flow. These indices showed consistent across-stream and downstream decreases which suggest removal of the freshwater signature by mixing. Baroclinic volume transport also decreased downstream, but the coastal flow still had an alongstream extent >1000 km.

REED, R.K., and J.D. SCHUMACHER. Current measurements along the shelf break in the Gulf of Alaska. *Journal of Physical Oceanography* 16(11):1985-1990 (1986).

Data from current moorings at four sites near the shelf break in the Gulf of Alaska are used to

present information on the flow, to examine the effects of local winds, and especially to investigate momentum transfer between the offshore and inshore circulation. Net flow at the shelf break in the central and western Gulf appears to be similar through the year, but it intensifies appreciably in winter in the northeast Gulf. Only records in the northeast Gulf suggest significant effects on flow by local winds. The eddy fluxes of momentum at the shelf break were extremely small. Although the offshore Alaskan Stream was previously found to transfer momentum toward shore, this flux apparently does not reach the shelf break and influence shelf waters. It appears rather that the gradients of heat and salt observed near the shelf edge result from offshore effects of the coastal flow.

REED, R.K., and J.D. SCHUMACHER. Physical oceanography. In *The Gulf of Alaska: Physical Environment and Biological Resources*, D.W. Hood and S.T. Zimmerman (eds.), DOC/NOAA, DOI, 57-75 (1986).

We review the state of both the circulation and the physical property knowledge for the Gulf of Alaska. The largest-scale feature we cover is the offshore boundary current. This current is relatively wide (~400 km) and slow (~30 cm/s) on the east side of the Gulf, but it narrows to less than 100 km from Kodiak Island westward, with peak speeds of ~100 cm/s. Although occasional large changes occur in the path, transport, and properties of the Alaskan Stream, high-frequency variability is not typical. The Stream may transfer heat and momentum into coastal waters, although the relative importance of this process has not been established. Other features covered by our review include a continental shelf circulation system which is generally separate from the Alaskan Stream. On the outer shelf, there is weak net flow, but circulation seems to be steered by the bathymetry in large troughs which transect the shelf. On the east side of the Gulf, the flow tends to be variable but is probably stronger in winter than in summer as a result of local wind forcing. Along the Kenai Peninsula there is a distinct narrow current flowing westward with typical speeds of 20 cm/s, but which can range as high as 100 cm/s in the fall. This rapid fall spin-up results from a maximum freshwater discharge in September-October, and is accompanied by surface salinities as low as 25 parts per thousand. Winds may constrain the relatively dilute flow along the coast. This geostrophic coastal flow first enters Shelikof Strait where the barotropic mode may be important, then continues west along the Alaska Peninsula. These features of coastal circulation are clearly seen in seasonal sea level cycles at various tide stations. Large interannual changes also occur in the Gulf of Alaska. In general, the wind regime along the coast produces downwelling at the coast rather than upwelling.

REED, R.K., J.D. SCHUMACHER, and L.S. Incze. Circulation in Shelikof Strait, Alaska. *Journal of Physical Oceanography* 17:1546-1554.

Extensive hydrographic surveys were conducted in Shelikof Strait in March and October 1985. The data are used to describe circulation and property distributions and the changes that occurred. The upper layer flows to the southwest throughout the year, but greatest speeds occur in fall when surface waters are least saline because of a maximum in freshwater discharge. The deep water has its source to the south, and the properties seem to result from

vertical mixing of this southern water. Thus Shelikof Strait has an estuarine-like circulation with a northward, deep inflow. Property distributions showed isolines were usually deepest on the right side of the channel looking to the southwest; greatest baroclinic speeds were often there also. Differential Ekman pumping may contribute to the development of this structure and its changes. Volume transport estimates varied considerably. In October the southwest flow bifurcated, with part continuing along the Alaska Peninsula and the rest exiting the main channel to the south; in March all upper-layer flow followed the main channel. Shelikof Strait appears to be a system influenced by both density-driven and wind-driven effects.

REED, R.K., J.D. SCHUMACHER, and L.S. Incze. Water properties and circulation in Shelikof Strait, Alaska during 1985. NOAA TM ERL PMEL-68 (PB87-143053), 35 pp. (1986).

Data from cruises in March, July, and October 1985 are used to describe circulation and property distributions, and their changes, in Shelikof Strait. The Alaska Coastal Current flows to the southwest throughout the year, but greatest baroclinic, geostrophic speeds occur in fall when the upper waters are least saline because of a maximum in freshwater discharge. The deep water in the central part of the Strait has its source to the south, and the properties seem to result from vertical mixing of this southern water. Thus Shelikof Strait has an estuarine-like circulation, but the intensity of the northward inflow varies appreciably. Property distributions showed isolines were nearly always deepest on the right side of the channel (looking downstream); greatest baroclinic speeds were often there also. It is believed that differential Ekman pumping may be important to the development of this structure and its changes, at least in some locations. Volume transport estimates for the upper 150 db varied greatly in space and time, with maximum values $>10^6$ m^3 s^{-1}. At times the southwest flow bifurcated, with part continuing along the Alaska Peninsula and the rest exiting the main channel to the south.

ROACH, A.T., J.D. SCHUMACHER, and P. STABENO. Observations of currents, surface winds, and bottom pressure in Shelikof Strait, Autumn 1984. NOAA TM ERL PMEL-74 (NTIS not yet available), 116 pp. (1987).

An extensive array of current meters and bottom pressure gauges was deployed in Shelikof Strait, Alaska, during 1984/85 as part of the Fisheries Oceanography Coordinated Investigations (FOCI). FOCI is aimed at understanding the physical and biological environment surrounding the early life stages of the Pacific pollock (*theragra chalcogramma*). These data, as well as calculated surface wind time series, were analyzed to investigate the influence of the Alaska Coastal Current (ACC) in this region. The ACC induced a strong mean flow (15 to 25 cm/s) during this season concentrated along the Alaska Peninsula on the northern side of the Strait. Outside the influence of the ACC, mean currents were weak (5-8 cm/s). This highly variable flow bifurcated in the vicinity of the Semidi Islands, with 75% of the ACC volume flux flowing seaward out of a deep (200+m) sea valley which meets the shelf break at a sill southwest of Kodiak Island. This strong outflow can induce an estuarine type circulation through entrainment of bottom water causing a mean inflow at depth. The re-

mainder of the flow continues along the Alaska Peninsula. The currents were generally well correlated in the vertical at each mooring, while the horizontal correlations were weak, indicating the horizontal spatial scales of coherence were less than the 8 to 15 km mooring separation. Surface winds from a location near the Barren Islands (200 km north of the Strait) showed the strongest relation to currents and transport. There was an indication that the winds drove the pressure differences and thereby the currents, as there was a significant correlation between bottom pressure differences and currents.

Schultz, A., J. Booker, and J.C. LARSEN. Lake bottom magnetotellurics. *Journal of Geophysical Research* 92(B10):10639-10649 (1987).

The study of the electrical conductivity structure of the lower crust and the upper mantle and midmantle promises to place important constraints on the thermobaric and compositional state of the earth's interior. Such work, particularly for depths above approximately 400 km, is best attempted by magnetotelluric sounding, an effort frustrated by the almost complete absence of stable long-period electric field measurements. In this paper, we propose that proven techniques developed for seafloor magnetotellurics be applied also to deep freshwater lakes. The establishment of such long-period electric and magnetic observatories in the thermally stable, low-noise lake bottom environment will yield new insights on the deep electrical structure beneath the continents. A lake bottom long-span electric field array was deployed in a deep freshwater lake adjacent to Seattle, Washington. A vector flux gate magnetometer was buried on the shore of the lake, and magnetotelluric data of high quality were collected. The analysis of the data described in this work clearly demonstrates the feasibility of establishing such lake bottom continental magnetotelluric observatories. Inversion of the data provides a view of structure beneath the site consistent with regional seismic and tectonic models.

Schultz, A., and J.C. LARSEN. On the electrical conductivity of the mid-mantle — I. Calculation of equivalent scalar magnetotelluric response functions. *Geophysical Journal of the Royal Astronomical Society* 88:733-761 (1987).

The problem of global conductivity sounding has been re-posed in order to investigate the possible existence of large-scale lateral heterogeneities in mid-mantle conductivity. A response function (Z/H) is robustly estimated and scaled into an equivalent scalar magnetotelluric impedance by assuming the geomagnetic field spatial variations are adequately described by P_1^0 spherical harmonic. Data found to be inconsistent with this representation in either the time, frequency or spatial domain are excluded from the analysis. Making use of this relationship, robust statistical techniques and careful data handling procedures have been applied to a new global magnetic database containing well in excess of 10^6 daily mean values (1358 observatory-years spanning the period 1883-1980). A set of spatially distributed scalar frequency domain impedance functions for a variety of tectonic provinces result from this analysis. Response functions consistent with both the P_1^0 assumption and local 1-D earth structure were found for 22 of the 79 observatories examined. The set of acceptable response

functions is presented, along with a summary of data quality for the observatories represented in the database.

SCHUMACHER, J.D. Description of the physical and biological environment (Rapporteur's Report). Proceedings, A workshop on Comparative Biology, Assessment, and Management of Gadoids from the North Pacific and Atlantic Oceans, NWAFC, Seattle, WA, June 1985, 13-18 (1986).

No abstract.

SCHUMACHER, J.D. Description of the physical and biological environment — Rapporteur's Report. *Fisheries Research* 5:111-118 (1987).

No abstract.

SCHUMACHER, J.D., and J.G. WILSON. On the atmospheric and oceanic environment of the Gulf of Alaska. Proceedings, A Workshop on Comparative Biology, Assessment, and Management of Gadoids from the North Pacific and Atlantic Oceans, NWAFC, Seattle, WA, June 1985, 135-178 (1986).

We review the state of knowledge of meteorology and physical oceanography in the Gulf of Alaska. We focus on processes that regulate transport, a factor which likely impacts recruitment and is operative during early life stages when fish, some of their predators and all of their prey are planktonic. The passage of low pressure systems dominates the meteorology, with an average of one storm every four or five days during winter. Associated with these storms are winds up to 40 m s^{-1}, persistent cloud cover, and up to 8 m of precipitation annually in the coastal mountains. Trajectories for low pressure systems are largely determined by the location and strength of three semi-permanent atmospheric features: the Aleutian low and Siberian high pressure systems in autumn, winter, and spring giving way to the east Pacific high pressure system in summer. Interaction between the high coastal mountains which ring the Gulf and the pressure systems results in significant local features including valley-drainage or katabatic winds, down pressure gradient or gap winds, and along-shore coastal wind jets. Both wind (coastal convergence) and freshwater addition (precipitation and runoff) are responsible for the dominant shelf current or Alaskan Coastal Current. Because there is a longitudinal variation in wind characteristics, there is also a vast difference in upwelling between the coasts of the eastern and western Gulf of Alaska. Oceanographic features also vary east to west. The largest-scale feature is the offshore boundary current, the Alaskan Stream which is relatively wide and slow (~30 cm s^{-1}) on the east side of the Gulf but narrows to less than 100 km near Kodiak Island and westward and has peak speeds of approximately 100 cm s^{-1}. On the continental shelf there is a circulation system which is generally separate from the Alaskan Stream. The outer shelf often has weak net flow, but circulation seems to be steered by the bathymetry in some large troughs which transect the shelf. On the east side of the Gulf, the flow tends to be variable but is stronger in winter than

summer as a result of local wind forcing. West of about 145°, there is a distinct narrow current flowing westward; it typically has speeds of 20 cm s^{-1} but may have values in excess of 100 cm s^{-1} in autumn. This rapid autumn spin-up is accompanied by surface salinities as low as 25‰ and results from a maximum in freshwater discharge in September-October. Winds act to constrain the relatively dilute flow along the coast. This geostrophic coastal flow enters Shelikof Strait, where the barotropic mode may be important, and continues west along the Alaska Peninsula. These features of coastal circulation are clearly seen in the seasonal cycles of sea level at tide stations. The large interannual changes that result from El Niño also penetrate poleward into the Gulf of Alaska.

STEELE, L.P., P.J. FRASER, R.A. Rasmussen, M.A.K. Khalil, T.J. CONWAY, A.J. Crawford, R.H. GAMMON, K.A. MASARIE, and K.W. THONING. The global distribution of methane in the troposphere. *Journal of Atmospheric Chemistry* 5:125-171 (1987).

Methane has been measured in air samples collected at approximately weekly intervals at 23 globally distributed sites in the NOAA/GMCC cooperative flask sampling network. Sites range in latitude from 90°S to 76°N, and at most of these we report 2 years of data beginning in early 1983. All measurements have been made by gas chromatography with a flame ionization detector at the NOAA/GMCC laboratory in Boulder, Colorado. All air samples have been referenced to a single secondary standard of methane-in-air, ensuring a high degree of internal consistency in the data. The precision of measurements is estimated from replicate determinations on each sample as 0.2%. The latitudinal distribution of methane and the seasonal variation of this distribution in the marine boundary layer has been defined in great detail, including a remarkable uniformity in background levels of methane in the Southern Hemisphere. We report for the first time the observation of a complete seasonal cycle of methane at the South Pole. A significant vertical gradient is observed between a sea level and a high altitude site in Hawaii. Globally averaged background concentrations in the marine boundary layer have been calculated for the 2 year-period May 1983-April 1985 inclusive, from which we find an average increase of 12.8 ppb per year, or 0.78% per year when referenced to the globally averaged concentration (1625 ppb) at the mid-point of this period. We present evidence that there has been a slowing down in the methane growth rate.

TENNANT, D.A., S.L. WALKER, J.W. LAVELLE, and E.T. BAKER. A practical manual for determining settling rates of ocean disposed sewage sludge. NOAA TM ERL PMEL-69 (PB87-178273), 29 pp. (1987).

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WILSON, J.G., and J.E. OVERLAND. Meteorology. In *The Gulf of Alaska: Physical Environment and Biological Resources*, D.W. Hood and S.T. Zimmerman (eds.), DOC/NOAA, DOI, 31-54, (1986).

The Gulf of Alaska is one of the most active meteorological regions on earth. The types of

weather found there are primarily caused by the passage of storm systems along the Aleutian storm track. Many of these storms are stalled by the high coastal mountains that ring the Gulf and are subsequently dissipated. Variability in the weather of the Gulf of Alaska is largely determined by planetary-scale motions, in particular by the presence of a high-pressure system that blocks the normal passage of storms. Large interannual variations are the norm. Throughout the year, offshore winds are predominantly from the south in the eastern Gulf, from the east in the northcentral region, and from the west, but highly variable, near the Aleutian Islands. Wind intensity is the greatest in the winter months of October through April. The nearshore wind field can be quite variable due to the presence of the high mountain barrier to onshore flow. Examples of nearshore wind phenomena include coastal wind jets, gap winds, and katabatic winds. Winter air temperatures over the ocean are generally warmer than at continental stations at the same latitude due to relatively warm ocean-water temperatures. Frequently during the winter cold, continental air will stream over the region, bringing a dramatic drop in air temperature. The Gulf of Alaska is almost always cloud covered and the precipitation away from the coast is on the order of 100 cm/y. Storms that cross the Gulf drop as much as 800 cm/y of precipitation in the form of rain and snow in the high coastal mountains. These mountains provide substantial storage for runoff. The weather in the Gulf of Alaska affects the regional oceanography by means of both wind-induced currents and coastal currents driven by differences in water density from the large runoff of fresh water along the coast of southeast Alaska. Because the weather influences the Gulf current systems and ocean stability, it has a major impact on the variability of the oceanic biological community.

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GLOSSARY OF ACRONYMS

ADCP:	Acoustic Doppler Current Profiler
AID:	Agency for International Development
AOML:	Atlantic Oceanographic and Meteorological Laboratory
APEX:	Arctic Polynya Experiment
ARGOS:	French satellite used to telemeter data to shore stations (not an acronym)
ASG:	Administrative Support Group
ATLAS:	Automated Temperature Line Acquisition System
CIRES:	Cooperative Institute for Research in Environmental Sciences
CIMRS:	Cooperative Institute for Marine Resources Studies
COADS:	Comprehensive Ocean-Atmosphere Data Set
CSG:	Computer Support Group
CTD:	Conductivity, Temperature, Depth
EDD:	Engineering Development Division
ENSO:	El Niño-Southern Oscillation
EOF:	Empirical Orthogonal Function
EPOCS:	Equatorial Pacific Ocean Climate Studies
ERL:	Environmental Research Laboratories
FAST:	Flow Actuated Sediment Trap
FGGE:	First GARP Global Experiment
FOCAL:	French Program Ocean-Climat Atlantique Equatorial
FOCI:	Fisheries-Oceanography Coordinated Initiative
FOCUS:	Fisheries Oceanography Cooperative Users System
FOX:	Fishery-Oceanography Experiment
GARP:	Global Atmospheric Research Program
GFDL:	Geophysical Fluid Dynamics Laboratory
GMCC:	Geophysical Monitoring for Climatic Change Division, ERL
GOES:	Geostationary Operational Environmental Satellite
HMSC:	Hatfield Marine Science Center
IAMAP/IAPSO:	International Association of Meterology and Atmospheric Physics/ International Association for the Physical Sciences of the Ocean
IGOSS:	International Global Ocean Services System
IOC:	International Oceanographic Commission
IRIS:	International Recruitment Investigations in the Subarctic
ITCZ:	Intertropical Convergence Zone
JIC:	Navy/NOAA Joint Ice Center
JIMAR:	Joint Institute for Marine and Atmospheric Research
JISAO:	Joint Institute for the Study of Atmosphere and Ocean
L-RERP:	Long-Range Effects Research Program
MARD:	Marine Assessment Research Division
MIZ:	Marginal Ice Zone

MIZEX:	Marginal Ice Zone Experiment
MMS:	Minerals Management Service, U.S. Dept. of Interior
MRRD:	Marine Resources Research Division
MSRD:	Marine Services Research Division
NCAR:	National Center for Atmospheric Research
NESDIS:	National Environmental Satellite, Data, and Information Service
NIC:	NOAA Information Center
NMC:	National Meteorological Center
NMFS:	National Marine Fisheries Service
NOAA:	National Oceanic and Atmospheric Administration
NOS:	National Ocean Service
NORPAX:	North Pacific Experiment
NWAFC:	Northwest and Alaska Fisheries Center
NWS:	National Weather Service
OAR:	Oceanic and Atmospheric Research
OCRD:	Ocean Climate Research Division
PENTAFLUX:	Fifth Flux Experiment
PEQUOD:	Pacific Equatorial Ocean Dynamics
PMEL:	Pacific Marine Environmental Laboratory
Ri:	Richardson Number, a dimensionless number related to stability of stratified flow
RJE:	Remote Job Entry
SCOR:	Scientific Committee on Oceanic Research
SEABEAM:	A shipboard multi-transducer swath echo sounding system
SLAR:	Side-Looking Airborne Radar
SLEUTH:	System for Locating Eruptive Underwater Turbidity and Hydrography
SLP:	Sea Level Pressure
S^3T:	Sequentially Sampling Sediment Trap
SST:	Sea Surface Temperature
STACS:	Subtropical Atlantic Climate Study
TAG:	Trans Atlantic Geotraverse
THRUST:	Tsunami Hazard Reduction Using System Technology
TOGA:	Tropical Oceans and Global Atmosphere
TOPS:	Total Ocean Profiling System
USGS:	United States Geological Survey
VENTS:	Name of hydrothermal venting research program (not an acronym)
WEPOCS:	Western Equatorial Pacific Ocean Circulation Study
WMO:	World Meteorological Organization
XBT:	Expendable Bathythermograph

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